3. REPUBLIC OF TAJIKISTAN

3.1. Optimization of Use of Water and Energy Resources in the Syrdarya Basin Under Current Conditions, G. Petrov and S. Navruzov

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1.1 Water Resources of the Syr Darya Basin

Kairakkum Reservoir is the only big reservoir of Tajikistan located in the Syr Darya basin and being a part of the multiple-purpose hydrocomplex. The Kairakkum hydrocomplex was put into operation in 1957. Tables 1-5 present the reservoir water balances with all components for years typical for water availability.

Main characteristics attributed to the reservoir operation mode for 1987-1999 is given in Table 6 and may be used in future calculations.

<u>Note</u>

1. The balances presented in the report should not be regarded as a basis for calculations as in the years concerned the Kairakkum hydrocomplex operated in the irrigation mode and did not meet the interests of Tajikistan that was not offered any appropriate compensation.
2. The balances demonstrate big discrepancy if to take into account the reservoir water storage. It means that the basic water release and storage data are not sufficiently accurate to build a mathematical model and require correction in the future.

Table 1
Water Balance of Kairakkum HPP's Reservoir for 1964
(water availability – 103% of the rate)

Months	FLOW (million m³)									Accumulation (+) Drawdown (-)	Elevation by the end of the month
	INFLOW				CONSUMPTION						
	To the section of Akjar station	Precipitation	DCF Inflow	Total inflow	For generating electricity	Idle Emptying	Evaporation	Water withdrawal by pumping stations	Total water withdrawal from reservoir		
January	772	0.71		772.71	1,031.8				1,031.8	-259.10	344,3
February	809	15.4		824.40	699.2				699.2	+124.80	344,8
March	1,030.8	9		1,039.80	750.4		11.6	14.47	776.47	+263.33	344,5
April	1,520	8.9		1,528.90	1,623.9		20.8	27.2	1,671.9	-143.00	344,25
May	1,801.7	6.7		1,808.40	1,849.2		70.9	52.2	1,972.3	-163.90	343,63
June	2,9581	4.4		2.962.50	1,680.9	38.85	98.9	70.7	1,889.35	+1073.15	343,25
July	2,951.9	2.1		2,954.00	2,023.4	345.72	107	81.4	2,557.52	+390.48	347,66
August	1,643			1,643.00	1,993.9	214.4	87.7	81.2	2,377.2	-734/20	346,55
September	946.2			946.20	1,377.9		60	65.8	1,503.7	-557.50	345,46
October	1,108.8			1,108.80	1,168.5		51	29.9	1,249.4	-140.60	345,16
November	1,129.8	0.4		1,130.20	1,124.1		24.7	19.3	1,168.1	-37.90	345,2
December	901.2	0.9		902.10	1,165.8		10.8		1,176.6	-274.5	344,73
Growing season	***11,820.90***	***22.10***		***11,843.00***	***10,549.20***	***598.97***	***445.30***	***378.50***	***11,971.97***		
Ungrowing season	***5,751.6***	***26.41***		***5,778.01***	***5,939.80***	***0.00***	***98.10***	***63.67***	***6,101.57***		
Mean value	***1,464***	***4.04***		***1,468.42***	***1,374.08***	***49.91***	***45.28***	***36.85***	***1,506.13***		
Annual total:	***17,572.50***	***48.51***		***17,621.01***	***16,489.00***	***598.97***	***543.40***	***442.17***	***18,073.54***	***-452.53***	

Table 2
Water Balance of Kairakkum HPP's Reservoir for 1971
(water availability – 103% of the rate)

Months	FLOW (million m^3)									Accumulation (+) Drawdown (-)	Elevation by the end of the month
	INFLOW				CONSUMPTION						
	To the section of Akjar station	Precipitation	DCF Inflow	Total inflow	For generating electricity	Idle Emptying	Evaporation	Water withdrawal by pump stations	Total water withdrawal from reservoir		
January	1,142	0.4	1	1,143.40	1,378	0	0	0	1,378	-234.60	346.31
February	961	6.2	0	967.20	1,269	0	20.6	0	1,289.6	-322.40	345.7
March	1,079	2.8	6.4	1,088.20	792	0	12.7	36.7	841.4	246.80	346.18
April	1,465	12.9	7.8	1,485.70	1,265	0	38.8	78.8	1,382.6	103.10	346.58
May	2,046	2.2	6.7	2,054.90	1,919	0	92.2	86.9	2,098.1	-43.20	346.71
June	3,268	0	6.3	3,274.30	2,137	727	105.8	90.8	3,060.6	213.70	347.33
July	1,533	0	6.7	1,539.70	2,131	0	100.9	98	2,329.9	-790.20	345.83
August	927	0	7.5	934.50	1,863	0	76.9	96.4	2,036.3	-1101.80	342.63
September	877	0	9.2	886.20	632	0	45.4	82.1	759.5	126.70	343.12
October	1,132	1.1	10.2	1,143.30	702	0	39.6	49.3	677.9	465.40	344.48
November	1,139	1	10.3	1,150.30	702	0	23.5	24.1	749.6	400.70	345.75
December	897	9.8	9.3	916.10	1,297	0	20.8	0	1,317.8	-401.70	344.83
Growing season	***10,116.00***	***15.10***	***44.20***	***10,175.30***	***9,947.00***	***727.00***	***460.00***	***533.00***	***11,667.00***		
Ungrowing season	***6,350***	***21.3***	***37.2***	***6,408.50***	***6,027.00***	***0.00***	***117.20***	***110.10***	***6,254.30***		
Mean value	***1,372***	***3.03***	***6.78***	***1,381.98***	***1,331.17***	***60.58***	***48.10***	***53.59***	***1,493.44***		
Annual total:	**16,466.00**	**36.4**	**81.4**	**16,583.80**	**15,974.00**	**727.00**	**577.20**	**643.10**	**17,921.30**	**-1,337.50**	

Table 3
Water Balance of Kairakkum HPP's Reservoir for 1973
(water availability – 105% of the rate)

Months	**FLOW (million m^3)**									**Accumulation (+) Drawdown (-)**	**Elevation by the end of the month**
	INFLOW				**CONSUMPTION**						
	To the section of Akjar station	Precipitation	DCF Inflow	Total inflow	For generating electricity	Idle emptying	Evaporation	Water withdrawal by pumping stations	Total withdrawal from the reservoir		
January	837	4.9	9.2	851.10	1,242.2	0	20	0	1,262.2	-411.10	345.84
February	886	9.7	9	904.70	813.3	0	0.5	0	813.8	90.90	344.88
March	995	9.6	10.9	1,015.50	887.1	0	14	13.2	914.3	101.20	345.22
April	1,735	10.5	14.3	1,759.80	1,493.2	0	26.4	67	1,586.6	173.20	345.66
May	2,780	6.4	13.6	2,800.00	2,284.7	451.3	72.2	81	2,889,.2	-89.20	346.1
June	3,347	0.8	14.4	3,362.20	2,127.5	838.8	112.3	80.6	3,159.2	203.00	346.57
July	2,204	0	17.7	2,221.70	2,165	561.7	108.2	105.1	2,940	-718.30	347.28
August	1,065	0	20	1,085.00	2,128.5	110.6	79.5	102	2,420.6	-1335.60	346.45
September	905	1.4	24.1	930.50	870.9	0	44.9	75.1	990.9	-60.40	343.43
October	1,123	0.1	25.5	1,148.60	762	0	22.3	48	832.3	316.30	342.33
November	973	2.5	23.3	998.80	687.1	0	23.2	39.2	749.5	249.30	343.39
December	743	0.5	20.6	764.10	830.6	0	8.2	0	838.8	-74.70	344.36
Growing season	***12,036.00***	***19.10***	***104.10***	***12,159.20***	***11,069.80***	***1,962.40***	***443.50***	***510.80***	***13,986.50***		
Ungrowing season	***5.557***	***27.3***	***98,.5***	***5,682.80***	***5,222.30***	***0.00***	***88.20***	***100.40***	***5,410.90***		
Mean value	***1,466***	***3.87***	***16.88***	***1,486.83***	***1,357.68***	***163.53***	***44.31***	***50.93***	***1,616.45***		
Annual total:	**17,593.00**	**46.4**	**202.6**	**17,842.00**	**16,292.10**	**1,962.40**	**531.70**	**611.20**	**19,397.40**	**-1,555.40**	

Table 4
Water Balance of Kairakkum HPP's Reservoir for 1974
(water availability – 51% of the rate)

Months	FLOW (million m^3)									Accumulation (+) Drawdown (-)	Elevation by the end of the month
	INFLOW				CONSUMPTION						
	To the section of Akjar station	Precipitation	DCF Inflow	Total inflow	For generating electricity	Idle Emptying	Evaporation	Water withdrawal by pumping stations	Total withdrawal from reservoir		
January	833	6.8	15.9	855.70	653.5	0	6.5	0	660	195.70	345.15
February	801	6.9	14.5	822.40	495.9	0	5.8	0	501.7	320.70	346.2
March	933	6.6	17.6	957.20	468.7	0	10.9	12.6	492.2	465.00	347.3
April	661	22.5	24.8	708.30	663.5	0	51.9	68.8	784.2	-75.90	347.15
May	581	6.6	25	612.60	1.001.7	0	82.3	93.3	1,177.3	-564.70	346.19
June	326	0.9	21.8	348.70	1,480	98.4	87.2	85.7	1,751.3	-1402.60	341.97
July	468	0.7	27	495.70	1,291	21.4	45	79.6	1,437	-941.30	336.46
August	936	1.5	30.8	968.30	723.2	375	16	71.3	1,185.5	-217.20	334.4
September	708	0.03	33.7	741.73	471.7	20.7	15.1	64.7	572.2	169.53	336.77
October	960	0.2	33.6	993.80	286.6	0	19.1	45.5	351.2	642.60	340.97
November	746	2.9	32.6	781.50	435.4	0	15.6	41.6	492.6	288.90	342.33
December	552	9.7	30	591.70	803.5	0	16	0	819.5	-277.80	341.93
Growing season	***3,680.00***	***32.23***	***163.10***	***3,875.33***	***5,631.10***	***515.50***	***297.50***	***463.40***	***6,907.50***		
Ungrowing season	***4,825***	***33.1***	***144.2***	***5,002.30***	***3,143.60***	***0.00***	***73.90***	***99.70***	***3,317.20***		
Mean value	***709***	***5.44***	***25.61***	***739.80***	***731.23***	***42.96***	***30.95***	***46.93***	***852.06***		
Annual total:	**8,505.00**	**65.33**	**307.3**	**8,877.63**	**8,774.70**	**515.50**	**371.40**	**563.10**	**10,224.70**	**-1,347.07**	

Table 5
Water Balance of Kairakkum HPP's Reservoir for 1978
(water availability – 81% of the rate)

Months	**FLOW (million m^3)**									**Accumulation (+) Drawdown (-)**	**Elevation by the end of the month**
	INFLOW				**CONSUMPTION**						
	To the section of Akjar station	Precipitation	DCF Inflow	Total inflow	For generating electricity	Idle emptying	Evaporation	Water withdrawal by pumping stations	Total water withdrawal from reservoir		
January	621	10.1	45.9	677.00	559	0	10.4	0	569.4	107.60	343.05
February	768.5	5.6	45.9	820.00	267.6	0	0	0	267.6	552.40	344.72
March	856	8	45.9	909.90	265	0	15.9	0	280.9	629.oo	346.38
April	1,053	20.5	45.9	1,119.40	434	0	45.3	24.5	503.8	615.60	347.49
May	965	16.2	45.9	1,027.10	1,560	0	75.9	43.5	1,679.4	-652.30	346.25
June	1,240	3.3	45.9	1,289.20	2,040	0	70,.2	62.8	2.173	-883.80	343.86
July	825	0	45.9	870.90	1,870	0	69	77.9	2,016.9	-1146.00	339.54
August	959	0	45.9	1,004.90	1,340	0	23	68.5	1,431.5	-426.60	336.05
September	618	0	34.3	652.30	473	0	15	57.2	545.2	107.10	336.88
October	738	0.2	11.1	749.30	271	0	13.1	35.3	319.4	429.90	339.62
November	665	4.4	14.1	683.50	252	0	12.5	6.6	271.1	412.40	341.54
December	842	5.4	17.5	864.90	290	0	10	0	300	594.90	343.71
Growing season	***5,660.00***	***40.00***	***263.80***	***5,963.80***	***7,717.00***	***0.00***	***298.40***	***334.40***	***8,349.80***		
Ungrowing season	***4,490.5***	***33.7***	***180.4***	***4,704.60***	***1,904.60***	***0.00***	***61.90***	***41.90***	***2,008.40***		
Mean value	***846***	***6.14***	***37.02***	***889.03***	***801.80***	***0.00***	***30.03***	***31,. 6***	***863.18***		
Annual total:	**10,150.50**	**73.7**	**444.2**	**10,668.40**	**9,621.60**	**0.00**	**360.30**	**376.30**	**10,358.20**	**310.20**	

Table 6.
Estimation Characteristics of Kairakkum Reservoir for 1987-1999

Year		January	February	March	April	May	June	July	August	September	October	November	December
1987	Inflow Q Inf. m3/s	322	378	347	500	389	397	620	227	259	518	702	693
	Release Q Rel.m3/s	330	321	300	321	352	627	705	632	205	131	137	638
	Upper Reach for the Beginning of the Year (m)	343.34	343.27	343.70	344.07	345.23	345.48	343.99	343.29	338.89	339.73	343.57	343.07
Year													
1988	Inflow Q Inf. m3/s	631	633	510	685	986	843	873	430	577	559	616	624
	Release Q Rel.m3/s	664	582	503	821	1001	1001	1000	673	627	500	500	500
	Upper Reach for the Beginning of the Year (m)	347.34	347.19	347.45	347.49	346.77	346.69	345.82	344.97	343.19	342.79	343.28	344.17
Year													
1989	Inflow Q Inf. m3/s	631	635	446	292	568	766	845	694	344	397	623	581
	Release Q Rel.m3/s	397	436	560	466	895	900	1069	747	287	240	240	326
	Upper Reach for the Beginning of the Year (m)	345.00	346.46	347.44	346.82	345.88	343.62	342.55	340.25	339.51	340.27	342.01	344.87

Year		January	February	March	April	May	June	July	August	September	October	November	December
1990	Inflow Q Inf. m3/s	523	573	442	410	412	260	508	557	344	514	683	649
	Release Q Rel.m3/s	391	534	449	385	487	704	827	647	255	247	416	450
	Upper Reach for the Beginning of the Year (m)	346.47	347.19	347.38	347.34	347.47	347.06	344.42	341.84	340.84	341.80	344.05	345.78
Year													
1991	Inflow Q Inf. m3/s	651	613	513	398	586	627	595	367	261	465	633	748
	Release Q Rel.m3/s	556	591	539	445	698	785	939	677	283	220	220	446
	Upper Reach for the Beginning of the Year (m)	346.91	347.43	347.54	347.40	347.15	346.54	345.64	343.18	340.14	339.86	342.47	345.44
Year													
1992	Inflow Q Inf. m3/s	637	640	580	386	819	509	395	344	265	539	654	820
	Release Q Rel.m3/s	661	593	686	496	583	738	758	646	230	186	597	555
	Upper Reach for the Beginning of the Year (m)	347.19	347.06	347.30	346.72	346.14	347.43	346.22	343.50	340.65	341.03	344.16	344.53
Year													
1993	Inflow Q Inf. m3/s	788	801	684	532	917	813	308	264	236	596	919	1130
	Release Q Rel.m3/s	596	744	845	468	811	892	797	649	318	274	537	826
	Upper Reach for												

	the Beginning of the Year (m)	346.25	347.30	347.58	346.70	347.04	347.62	347.20	344.20	340.74	339.79	343.07	345.72
Year													
1994	Inflow Q Inf. m3/s	1031	1027	969	810	936	388	391	302	605	589	846	1155
	Release Q Rel.m3/s	1084	997	1013	939	802	780	743	557	367	526	737	653
	Upper Reach for the Beginning of the Year (m)	347.43	347.14	347.29	347.05	346.37	347.10	344.81	342.09	339.97	341.85	342.41	343.28
Year													
1995	Inflow Q Inf. m3/s	1044	953	778	422	229	160	372	253	195	418	653	967
	Release Q Rel.m3/s	940	1022	815	507	398	400	586	423	206	252	468	724
	Upper Reach for the Beginning of the Year (m)	346.64	347.21	346.87	346.67	346.22	345.14	343.49	341.62	339.61	339.44	341.46	343.08
1996	Inflow Q Inf. m3/s	982	901	832	700	405	611	314	287	268	498	855	1103
	Release Q Rel.m3/s	672	731	894	611	542	549	623	576	266	452	614	739
	Upper Reach for the Beginning of the Year (m)	344.88	346.78	347.62	347.28	347.78	347.07	347.40	345.65	343.65	343.67	344.04	345.60
1997	Inflow Q Inf. m3/s	1038	974	765	563	320	301	316	268	192	251	618	899
	Release Q Rel.m3/s	1047	1002	930	406	397	450	548	442	183	256	490	636
	Upper Reach												

	for the Beginning of the Year (m)	347.66	347.62	347.47	346.57	347.40	346.98	346.19	344.68	343.39	343.46	343.42	344.36
Year													
1998	Inflow Q Inf. m3/s	974	997	905	552	717	1022	502	303	291	522	714	998
	Release Q Rel.m3/s	844	886	971	448	704	1031	705	608	274	577	916	651
	Upper Reach for the Beginning of the Year (m)	346.10	346.81	347.36	347.00	347.55	347.62	347.57	346.46	344.52	344.63	344.26	342.70
1999	Inflow Q Inf. m3/s	1134	1001	858	891	521	347	421					
	Release Q Rel.m3/s	897	920	900	744	556	504	619					
	Upper Reach for the Beginning of the Year (m)	345.27	346.70	347.10	346.87	347.65	347.46	346.63					

1.2. Irrigation Development in the Basin

Artificial irrigation in Central Asia ascends to great antiquity. It developed through six thousands of years, and irrigation methods and technique, water withdrawal from the sources and regulation of water diversion gradually improved. Irrigation canal tracks were built and their maintenance ameliorated; the irrigated areas extended, and crop structure took a turn for the better. The peoples of Central Asia were hot upon the cause; they spent their creative power, talents and knowledge. Popular experience that was dedicated to creation of irrigation systems was handed down and enriched from generation to generation. A. Middendorf, a famous Russian scientist, in his essay about the Fergana Valley (1882) wrote about a high level of excellency of ancient irrigators in Central Asia: "We are amazed when see that the nation so technically undeveloped was able to divert to their fields water from a precipitous mountainous area, on the distance of 15 miles, passsing by mountains and valleys; but the thing that the works are done without any leveling knowledge, with no instrument needed for that provokes a greater surprise; we are surprised seeing smaller canals gradually descending to the valley along heughs, on the half height of them, and cut out in the hard rocky mass; seeing tunnels that carry water…".

It was found out that the lands on which we may see the traces of ancient irrigation with extant canals, tillable furrows, ruins of ancient settlements and fortresses occupy the area of 8-10 million hectares, approximately equal to the present-day irrigated area (Andrianov and Kes, 1967).

History of irrigation of Central Asia abounds in periods of heyday and fall of the irrigation management.

Gradual development of irrigation systems and expansion of irrigated areas in almost all Central Asian regions was observed as long as the middle of the first millennium, CE. The ancient irrigation network of the fourth millennium, BC, was found in the Tedjen delta (Lisitsina, 1965).

In the third and second millenniums, BC, irrigation was developing on the lands of the lower Amu Darya, Zarafshon and other Fergana rivers (Gulyamov, 1956, Latynin, 1962). In the middle of the first millennium, BC, an original irrigation system in the Atrek basin, on the area of ancient Messirian came into being (Masson, 1964). In the sixth and fifth centuries, BC, irrigation in the Zarafshon Valley reached the golden age. . The lands on the Zarafshan's lower reaches, where we can find the traces of ancient irrigation as much as twice exceed the existing irrigated oasis (Shishkin, 1963). In the fourth – second centuries, BC, in the era of Horezm's peak farming culture the irrigated farming evolved in the Murgab and Tedjen basins (Masson, 1959), in the deltas of the Talas, Chu, Ili and other rivers of Semiretchye[1], on the areas of the Syr Darya upper reaches and tributaries. Chronographers of ancient Greece, and Arabian historians and geographers witnessed the existence of big irrigation canals in the Chirchik and Angren valleys as long ago as the third and the second centuries, BC. Some of them – Zakh, Iskander, Bozsu, Karosu, Salar –have survived to this day. Over 50 settlements (Tashkent is among them) surrounded by the irrigated oases, orchards and vineyards were built on the base of those canals.

[1] Region of seven rivers

Beginning from the middle of the first millennium, CE, iterative periods of collapse and decline are appending to irrigation of Central Asia. The invasions of nomadic Khionites[2] (the fourth century) and Mongols (the eighth century) caused new destruction of the irrigation systems and desolation of huge territories. Subsequent continuous and devastative feudal wars were detrimental to the irrigation of Central Asia.

Irrigation activities were reanimated after Middle Asia joined Russia (Mamedov, 1965, 1967).

The irrigation area of all Central Asia before the Revolution[3] was about 2 million hectares.

Already in the first year after the Revolution, signed by Lenin hysterical Decree of the Soviet Government, of 17 May 1918, *On Allocation of 50 Million Roubles for the Irrigation Works in Turkestan and Work Arrangement* laid the foundation of enhanced and balanced irrigation construction and land irrigation in all Soviet Republics of Middle Asia.

The first water construction projects in Middle Asia in the late twentieths and early thirtieths solved the problems of primary concern to improve water supply for old arable lands (Askotchenskiy, 1967). However the projects were autonomous from the general program of complex use of water sources. After the in-depth study of land, water and hydropower resources and conducting extensive research in the area of irrigation and irrigated farming in the first time in the thirtieths scientifically established schemata were developed relating to complex irrigation and energy uses of water resources.

We know that irrigation mainly "consumes" water for agricultural needs during a summer growing season, in other words, irrigation refers to the group of water consumers. The size of potential irrigated area depends upon available water resources and their in-year distribution.

The in-year flow distribution of Central Asian river waters is generally productive for irrigation needs. Therefore, during some time natural river regime satisfied those needs, and water management measures were local. In other words, they were separate individual decisions and did not add up. They did not form the phenomenon that might be called a water management system.

As the irrigation lands expanded, measures intended to reallocate water resources, spatially and in time, became more and more important. Numerous main canals and reservoirs came into being (Askothensky, 1967; Alekseevsky, 1967). Simulteneously, hydropower plants were built to use energy resources of the rivers (Zakhidov, 1962, 1963).

Development of water management and enlargement of water systems caused some sectoral complexity of the relations (chiefly between irrigation and hydraulic power) and tangled the interrelations among the elements of the water complex (reservoirs, diversion structures, hydropower and pump stations, etc.). Efficient planning and certain water management measures were not possible without their integration into one aggregate within the water complex, and the operation of the complex was impossible without centralized control.

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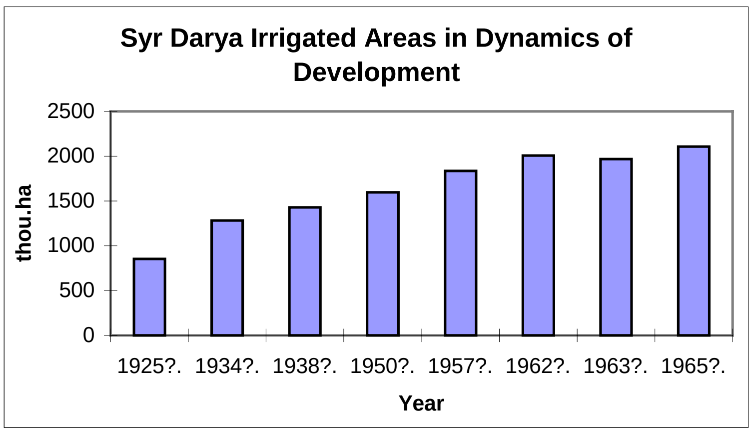
[2] The spelling of the word is approximate (the translator's note)
[3] Great October Socialist Revolution

The basin of the Syr Darya crossing the territories of three Central Asian countries (Kyrgyzstan, Tajikistan and Uzbekistan) and the territory of South Kazakhstan includes 497 "stationary" rivers (with the exception of the Naryn with all tributaries upstream from Uch-Kurgan section) that run for a length of 10 and more kilometers. The total length of these rivers is 14,750 km. About 1000 irrigation canals with a length of 53.5 thousand km and over 300 collectors are built and operated in the basin. The total extension of the drainage collector network is 31.5 thousand km. The uniform water management system established within the basin in 1966 covered the area of 0.53 million km with population of 13.5 million people, including 5.8 million of urban and 7.7 million of rural residents. Urban population is concentrated in 39 towns and 110 urban villages. Total land fund within a water management system is shown in Table 1 (A. Zakhidov, 1971).

The Syr Darya irrigated areas in dynamics are as follows (A. Zakhidov, 1971):



Year	Irrigated Area, thou.ha
1925	854
1934	1283
1938	1427
1950	1598
1957	1836
1962	2007

The irrigated lands of the Aral Sea basin in dynamics of development, from 1986 to 1996, are presented in the WARMIS database.

Table 1.
Development of Irrigated Lands of the Aral Sea Basin from 1986 – 96, (from WARMIS database).

Water Management Area	Area, thousand ha			
	Gross Area	Fit for Irrigation	Currently Irrigated (1965 г.)	Potential Enlargement
Upper Naryn	7000	170	130	40
Fergana Valley	7800	1370	980	390
Golodnaya Steppe	2200	1050	410	640
Chakir	3400	660	350	310
Artur	10700	1300	130	1170
Lower Reaches	22000	1600	107	1493
Total	**53100**	**6150**	**2107**	**4043**

The Syr Darya is the longest river of Central Asia. It is formed by the convergence of the Naryn and Kara Darya. The Syr Darya together with the Naryn runs for a length of 2,671 km. The Naryn's normal annual flow at Uch Kurgan is 417 m^3/s, and the Kara Darya's at Kampyrravat is 123 m^3/s. The extreme values of the Naryn's annual average discharges are 540-267 m^3/s, the Kara Darya's are 207-69.7 m^3/s. As the Naryn forms 77% of the Syr Darya flow, and the Kara Darya forms 23%, the Syr Darya, especially Upper Syr Darya, reflects the Naryn's regime.

The Naryn (the headwater zone coming out of the mountains), Kara Darya and obviously Syr Darya are called the rivers of glacial and snow feeding (the maximum flow is in June and the minimum flow is in January-February). However, the Naryn having higher catchment levels (the weighted average height H_{av} is 2,775 v), and therefore, its flow is concentrated later than the Kara Darya's flow (H_{av} = 2,599 m). The Naryn's flow in June is 45.2%, the Kara Darya's is 53%, for July-September the annual flows are 35.9% and 29%, correspondingly. The Syr Darya is formed by the convergence of the main tributaries within the boundaries of the Fergana Valley.

The rivers of the south-western slope of the Fergana Mountains are the Kara Darya's right tributaries (A. Zakhidov, 1971). They are Yassy (34.35 m^3/s,) Kugart (22.8 m^3/s), Kara Ungur (31.6 m^3/s) and Mailissu (8.7 m^3/s).

The Kara Darya left tributaries are the rivers of the northern slope of the Alai Mountains: Kurshab (25 m^3/s), Taldyk (1.2 m^3/s), Ak Bura (22.6 m^3/s), Aravansai (14 m^3/s), Abshirsai (1.7 m^3/s).

The Syr Darya's right tributaries are the rivers flowing from the steeps of the Chatkal Mountains and Kuramin Mountains. They are 16, if not counting a great number of sais[4] with a probable flood flow discharge from 20 to 170 m^3/s. The most water-bearing tributaries are Kasansai (11.5 m^3/s), Padshaata (8.7 m^3/s), Gavasai (6.1 m^3/s) and Chaadaksai (4.4 m^3/s).

[4] Sai is a transient water stream formed in natural depressions (gullies, ravines, canyons, crevices).

The Syr Darya's left tributaries flow from the northern slope of the Alai and Turkestan Mountains. The largest are Sokh (45.9 m^3/s), Isfairam (22.3 m^3/s), Isfara (15.7 m^3/s), Khodza Bakirgan (11.0 m^3/s), Shakhimardan (9.8 m^3/s) and Aksu (4.6 m^3/s). (A. Zakhidov, 1971).

After the Syr Darya comes out from the Fergana Valley a quantity of rivers, streams and sais flow into it from the northern hillside of the Turkestan and Nurat Mountains. The discharges of water streams are measured by the tens of liter per second. They are all taken out for irrigation during the growing season. The largest are Zamani and Sanzar with normal discharges of 2-4 m^3/s. The extreme values of the annual average flow of the Syr Darya basin rivers are 49-26.6 km^3.

The following water management activities were implemented to ensure stable water diversion and improve the reclamation conditions of 2 million hectares of the irrigated lands in 1971 (A. Zakhidov) within the boundaries of the Syr Darya water system:

- Large irrigation canals that divert water from the Naryn, Kara Darya and Syr Darya are constructed. They are the Big Fergana Canal (BFC) (named in honor of U. Yusupov; the head carrying capacity is 185 m^3/s), the South Fergana Canal (SFK, 50 m^3/s), the supply canal ensuring water diversion into the Shakhrikhansai Canal (150 m^3/s), Andishansai Canal (54 m^3/s), Savai (20 m^3/s), Akhunbabaev Canal (50 m^3/s, South Golodnostepski Canal (300 m^3/s), Northern Golodnostepski Canal (named in honor of Kirov, 230 m^3/s). Dalvarzin Canal (78 m^3/s), etc.
- The barrages have been constructed: The Uch Kurgan Dam on the Naryn River, Kampyrravat, Teshiktash and Kuiganyar dams on the Kara Darya, the Kairakkum, Farkhad, Chardara, Kzyl Orda and Kazalinsk dams on the Syr Darya River; Kairakkum Reservoir (4.16 km^3) and Chardara Reservoir (5.7 km^3) have regulated the Syr Darya flow.
- To improve irrigation use of the Kara Darya and Syr Darya tributaries and increase irrigated areas the mains have provided various interbasin flow diversions: the Oturzadyr Canal contributed to flow diversions between the Ak Bura and Kurshabsai rivers; the canal and Naiman off-stream reservoir (40 million m^3) afforded diversions between the Aravansai and Abshirsai rivers; the Lyagan canal, named in honor of the 18th Party Congress, provided diversions between the Isfairam and Shakhimardan; the Sokh Shakhimarda Canal (SSC) implements the diversions between the Shakhimardan and Sokh rivers. The following other canals provided diversions:
  The canal and Karkidan Reservoir (100 million m^3) between the SFC and Isfairamsai;
  The canal and Ortotokoy Reservoir (100 million m^3) between the Kasansai and Alabuka;
  The Chust Canal between Sumsarsai, Koksareksai and Gavasai;
  The Karasu Canal, Big Tashkent Canal and Tuyabuguz Reservoir (250 million m^3) between the Chirchik and Angren;
  The Arys-Turkestan Canal with Bugun Reservoir (370 million m^3) between the Arys and Bugun.
- Numerous pump stations have been built to irrigate high lands. The biggest of them are Andusamad, Frunze, Khodzha Bakirgan, Samagor, Haus and Unzhin pump stations.

- An extensive network of drainage collector and discharge canals exists (the Severo Bagdad Canal, Sokh Isfarin, Sary Dzhuga, Middle Kazyl Tepin, Yazyavan, Ulugnar, Zambarkul, Shokul canals; Main (flood-land) Karasu Canal, Urtukli Canal and others. Some of these collectors both drain the adjacent irrigated lands and receive into their streambeds water lost in the pebble sediments above the debris cone. They also receive the flows of the above mentioned rivers during the vegetation period.
- Potential hydropower resources of the Syr Darya Basin are estimated as much as 21.8 million kWh (Zakhidov, Chernova, 1963; Bolshakov, 1960; Kalachev et al, 1958).

So then, on the rivers of the Syr Darya Basin 25 relatively big district and several tens of small rural hydropower plants of 776.7 thou. kWh total installed capacity have been built. They are Uch Kurgan HPP (on the Naryn, 180 thou. kWh); Kairakkum HPP (126 thou. kWh), Farkhad HPP (114 thou. kWh), and Chardara HPP (100 thou. kWh) constructed on the Syr Darya River; the 16-HPP Cascade on the Chirchik Bozsu water tract.

By now, large work was carried out to extend and improve the Syr Darya water management complex. For instance, Toktogul Reservoir (12.6 km^3 of dischargeable capacity) and a hydropower plant of 1.2 million kWh capacity were built on the Naryn River; Andizhan Reservoir (1.75 km^3) and a hydropower plant (100 thou. kWh) on the Kara Darya River; Charvak Reservoir (2 km^3) and a hydropower plant (600 thou. kWh) on the Chirchik River.

Thus, irrigation and reclamation of the virgin lands of Golodnaya and Djizakskaya steppes, the Karakum Canal's zone, rice-plant areas on the Lower Syr Darya and Lower Amu Darya lands are on the one hand unique activities in the world practice as they comprehensively solve social and economic problems and create irrigation, drainage and other social infrastructure. On the other hand, this large-scale "nature conquest" has brought to a grievous environmental situation in the Aral Sea Basin.

1.3. Formation of the Naryn-Syr Darya Cascade of Reservoirs and its Impact on the Irrigation and Hydropower Development

Up to recent time the Central Asian countries ran water resources of the Syr Darya and Amu Darya basins in the frameworks of distribution and viewed the region as the area governed from one center.

Today, after the collapse of the Soviet Union both political and economic systems of the Central Asian countries changed.

After the countries have declared independence, each country of the region is striving for the maximum use of the water resources available in the home river basins reasoning from internal economic and political interests. It gives a new twist to the problem of complex water uses. In the first place, the solution should consider a country independence and developing market conditions.

If to view it as one single statement, then the problem and a corresponding model are vary complicated. One of the most difficult issues regarding optimization of water and energy uses in a big region is to single out major goals and determine relative importance of each of them.

Each country and the whole region have, as a rule, several not compatible goals that change in time. It is very difficult to assess some of these goals quantitatively, and those, which are assessed, are often expressed by incompatible units. All this raises the problem. While planning water uses it is very difficult to find a successful combination of incompatible and very often conflicting goals, problems and imposed complex constraints and present it as one single system.

In practice, such complex polygonal problems are usually solved within the framework of the systems analysis. This allows separation of complex phenomena into smaller and clearer constituent subsystems. First, we may analyze those constituents and then, study relationships among them. Thus, the method of the systems analysis promotes maximum results at minimum labor inputs and costs.

In our case, taking into account the political situation in the region it is expedient to take **"national models"** as primary initial model blocs that optimize water and energy uses within the country.

In other words, when developing the optimization model of the Syr Darya basin we keep to the principle "from simple to complex", i.e. consider the initial development of national models and then, their mating within the general basin model.

For Tajikistan such a national model is the optimization model to manage the operation mode of Kairakkum Reservoir.

Let us formulate its basic statements.

- Major objective: maximum electricity generation in the ungrowing season;
- The reservoir operation mode: independent regulation;
- Consideration of irrigation interests: aggregate inflow and constraints imposed by the regimes of pump stations;
- Initial conditions: maximum level by the beginning of the nonvegetation period;
- Source data:
    - Reservoir morphological characteristics;
    - Assigned inflow to the reservoir;
    - HPPs' technical data;
    - Morphological characteristics of the reservoir bed;
    - Lower reach characteristics;
    - Information needed for calculations and interpretation of the results.

The models developed according to this scheme allow establishing optimal national regimes of use of the flows to the reservoirs (among all are the flows to Toktogul and Kairakkum reservoirs). Undoubtedly, they will be incompatible with each other.

Several options are possible to integrate them in one bloc.

One option is to use the GAMS code proposed by the US Agency for International Development (USAID)/Environmental Policies and Institutions for Central Asia (EPIC) Program. Unfortunately, it is badly fit for practical use as it is developed for a single space of all republics and thus in principle, does not consider interests of independent countries. It does not enable to give the opportunity to fairly compare losses and benefits of independent branches (above all, irrigation), and finally, it has a pure formal objective function with an arbitrarily assigned weighting coefficient and with lack of any objective base.

In the second variant an economic part is added to the original version of the program. The objective function maximizing the total gain is filled with real sense and becomes logically clear. There is an opportunity to compare without bias the activity results of different economic branches. This variant undoubtedly enables to formally optimize water and energy uses of the basin.

However, when making an effort of its practical implementation almost insuperable hindrances may occur and they are tied with the existing pricing and tariff policy in the region.

Currently, Central Asia does not even have a common electricity market to say nothing of other branches. As a result, prices for products and services substantially differ not only among the republics but also on the internal and external market, and in addition, they are not time-constant. Some other complexities also have a place. For example, it is impossible to isolate hydropower in power engineering, but right this kind of energy interests us. It is not clear both how to define the hydropower role in associate costs regarding frequency regulation, electricity transit, purchase and sale, and others. Similar situation occurs if to mention other types of products, agricultural products are among them.

And finally, even if to overcome all above complexities the model common for the region does not allow accounting for already existing relations among/between our countries. In other words, this model does not take into account a concrete supply-to-demand adjustment for products and services, conjuncture of prices in the world, and etc.

With regard to all this, the third variant that unites national models with the help of the standard market tool appears to be most real for practical use.

Optimal flow "regimes" (use regimes for Kyrgyzstan and Tajikistan and consumption regimes for Kazakhstan and Uzbekistan) serve the basis for it. The first conditions determine supply and the next conditions determine demand. The balanced prices appear as a result of bidding.

Of course, here we also have certain difficulties; for example, difficulties tied with the compensating flow regulation by Toktogul and Kairakkum reservoirs. Under these regulation conditions Toktogul and Kairakkum together regulate flow seasonally, and only Toktogul regulates an over-year flow. Nevertheless, this variant is practically expedient, as it is in no way impairs independence, it considers market relations and promotes their development in the region.

To some respect, the pricing issue is off as it isolates itself on the national level.

The above statements regarding national models and their mating with the use of market are the necessary but still the first step.

Undoubtedly, a general regional optimization model of the basin should be simultaneously developed and include the economic bloc. Its practical use will depend upon the degree of development of Central Asian common market.

As we noted, the Kairakkum hydrosystem is a multi-purpose system. Its main objectives are to generate electricity and seasonally regulate the irrigation flow. The main hydrosystem indices are presented in Table 1.

Table 1.
Kairakkum Hydrosystem Main Characteristics.

Floor Storage ($km^{3)}$	Operating Storage (km^3)	Dead Storage (km^3)	HPP's Capacity (MW)	HPP's Efficiency %	Normal Maximum Operating Level (m)	Turbine Q^{max} (m^3/s)
3.5605	2.6895	0.871	126	0.86	347.8	960

For further calculations we need link curves for the hydrosystem parameters, including the reservoir and hydropower plant. They are shown in Tables 2-7.

Table 2.
Dependence of H = f(W)

No.	H (m)	W (Mm^3)	No.	H (m)	W(Mm^3)
1	328	0	12	339	548.18
2	329	0.362	13	340	749.6
3	330	0.724	14	341	990.2
4	331	8.51	15	342	1230.8
5	332	16.3	16	343	1554.4
6	333	40.6	17	344	1877.9
7	334	65	18	345	2277.9
8	335	126.6	19	346	2677.9
9	336	188.1	20	346.5	2923.1
10	337	301	21	347	3168.3
11	338	414	22	347.5	3560.5

Table 3.
Dependence F = f(W)

No.	F(km^2)	W(Mm^3)	No.	F(km^2)	W(Mm^3)
1	166	414	12	357	1554
2	182	497	13	387	1716
3	198	582	14	410	1878
4	213	666	15	429	2078
5	230	750	16	445	2278
6	245	870	17	460	2478
7	262	990	18	476	2678
8	283	1111	19	493	2923
9	306	1231	20	514	3168
10	321	1393	21	550	3463

Table 4.
Dependence H = f(Q)

No.	H (m)	Q(m^3/s)	No.	H (m)	Q(m^3/s)
1	325.65	100	12	327.06	600
2	325.8	150	13	327.17	650
3	325.96	200	14	327.28	700
4	326.13	250	15	327.4	750
5	326.27	300	16	327.53	800
6	326.43	350	17	327.7	850
7	326.55	400	18	327.8	900
8	326.99	450	19	327.97	950
9	326.83	500	20	328.12	1000
10	326.95	550	21		

Table 5.
Dependence q = f(H_{net})

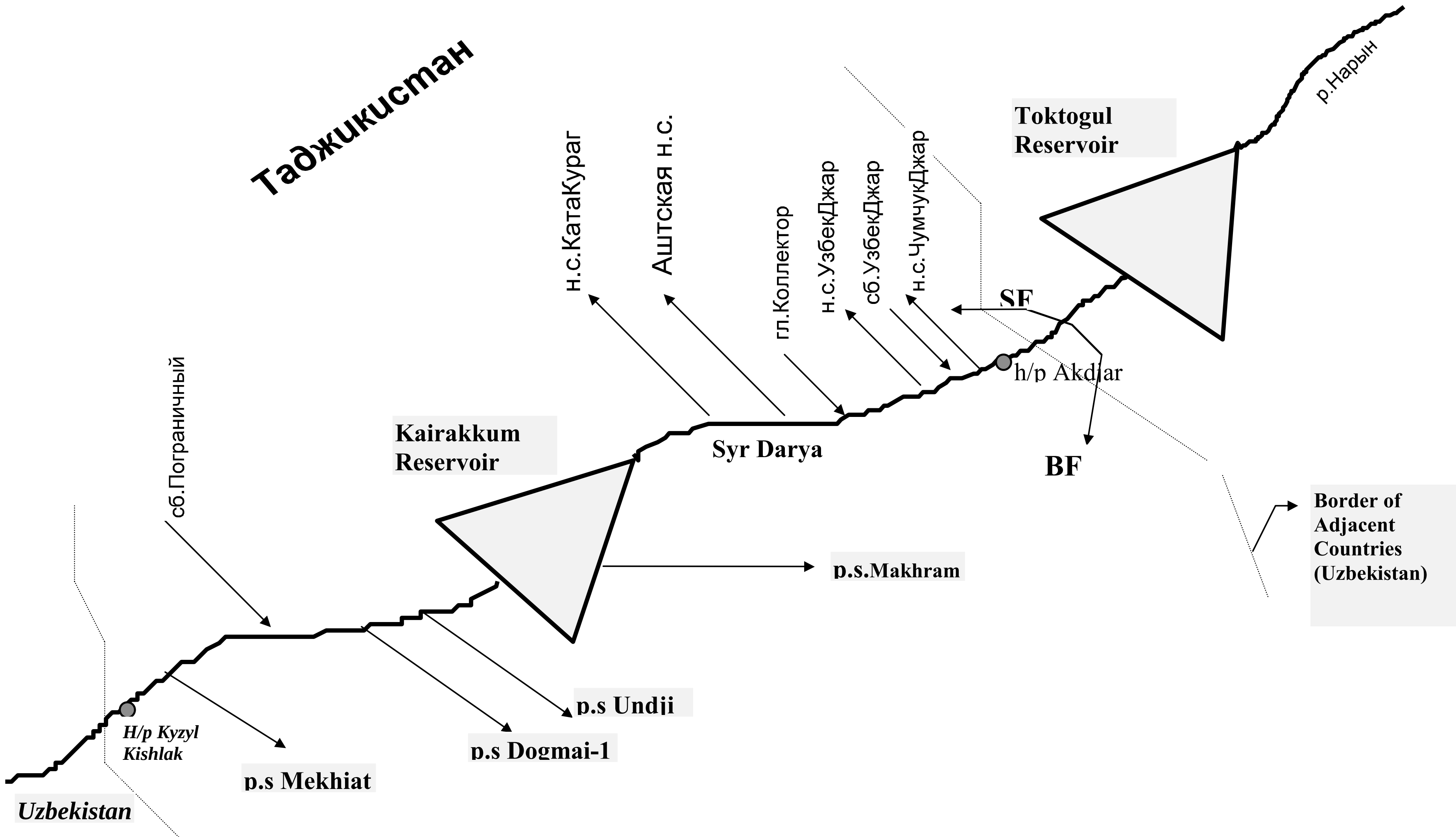
No.	Q(m^3/kWh)	H_{net} (m)	No.	Q(m^3/kWh)	H_{net} (m)
1	41	12.5	12	25.9	17.5
2	38	13	13	25	18
3	36	13.5	14	24	18.5
4	34.4	14	15	23.3	19
5	33	14.5	16	22.6	19.5
6	31.7	15	17	22.2	20
7	30.4	15.5	18	21.7	20.5
8	29.2	16	19	21.2	21
9	28	16.5	20		
10	27	17	21		

Table 6. Dependence Q_{max} = f(H_{net})

Table 7. Dependence η = f(H_{net})

No.	Q_{max}(m^3/s)	H_{net} (m)	No.	η	H_{net} (m)
1	900	14	1	0.764	12
2	924	15	2	0.802	13
3	948	16	3	0.82	14
4	978	17	4	0.829	15
5	918	18	5	0.837	16
6	876	19	6	0.843	17
7	828	20	7	0.85	18
8	795	21	8	0.854	19
9	756	22	9	0.856	20
10	732	23	10	0.857	21

Layout of the Syr Darya Basin at the Site Downstream to Kairakkum Reservoir



Calculation Diagram for the Kairakkum Operation (Tajik National Model)

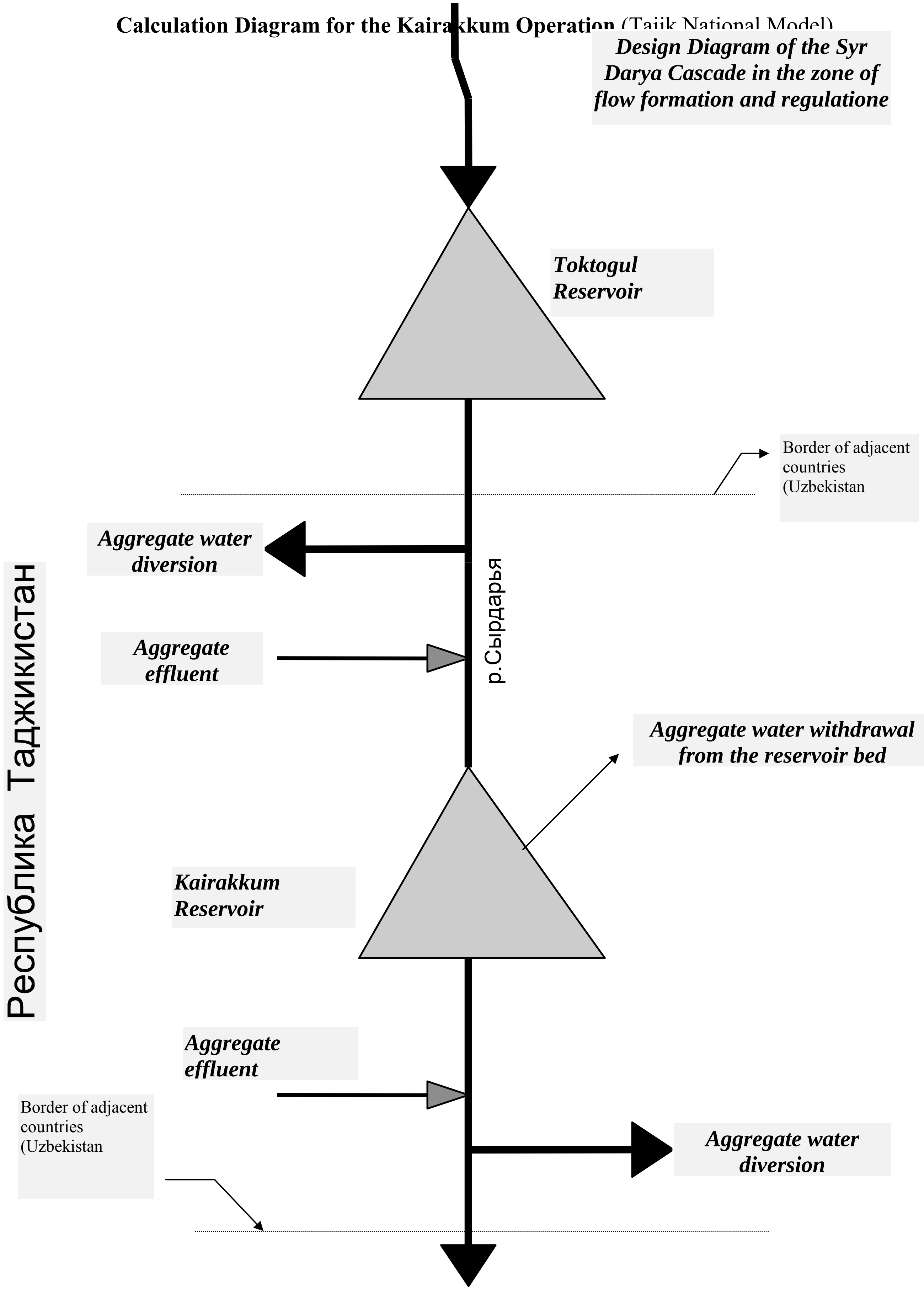
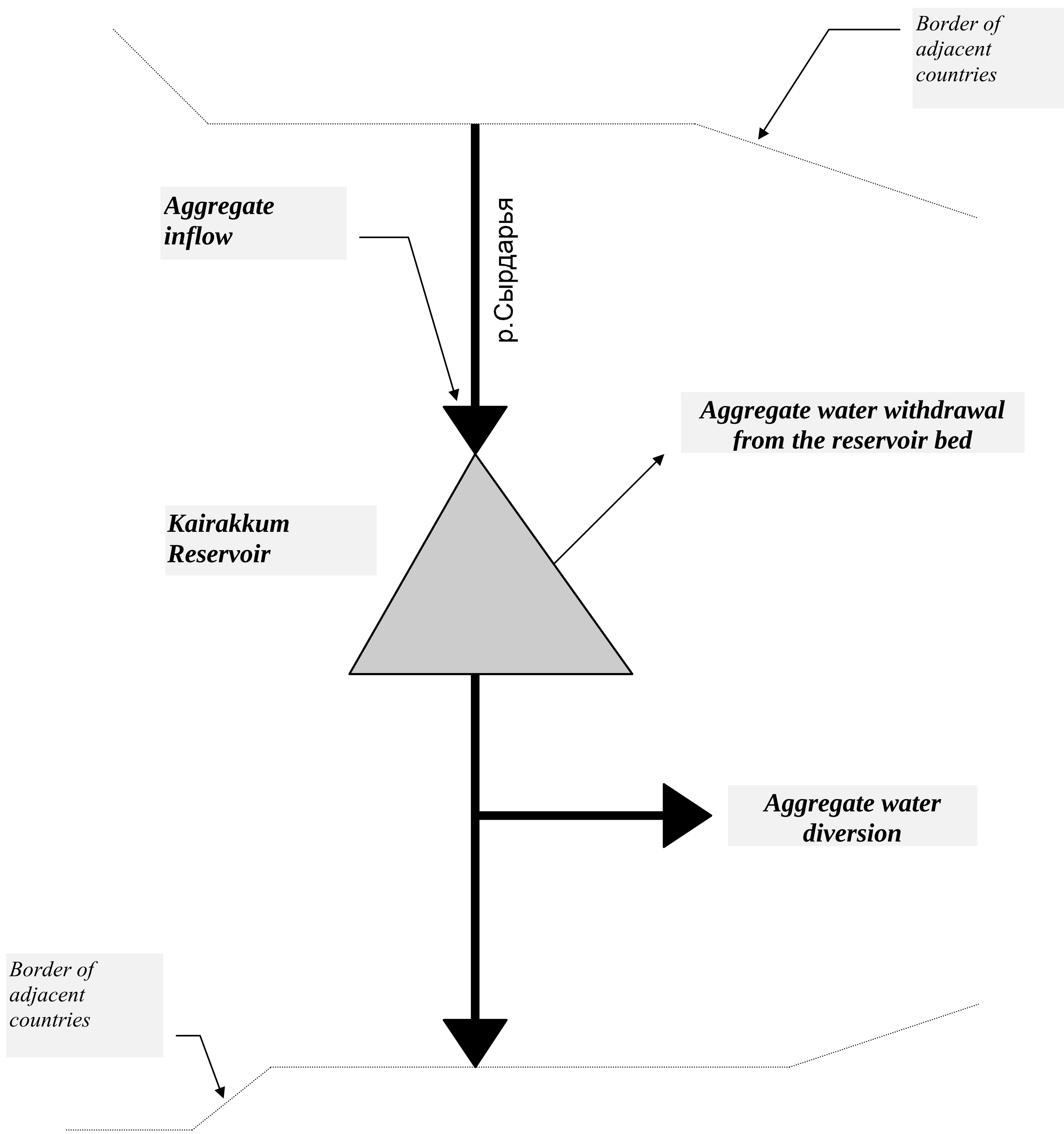
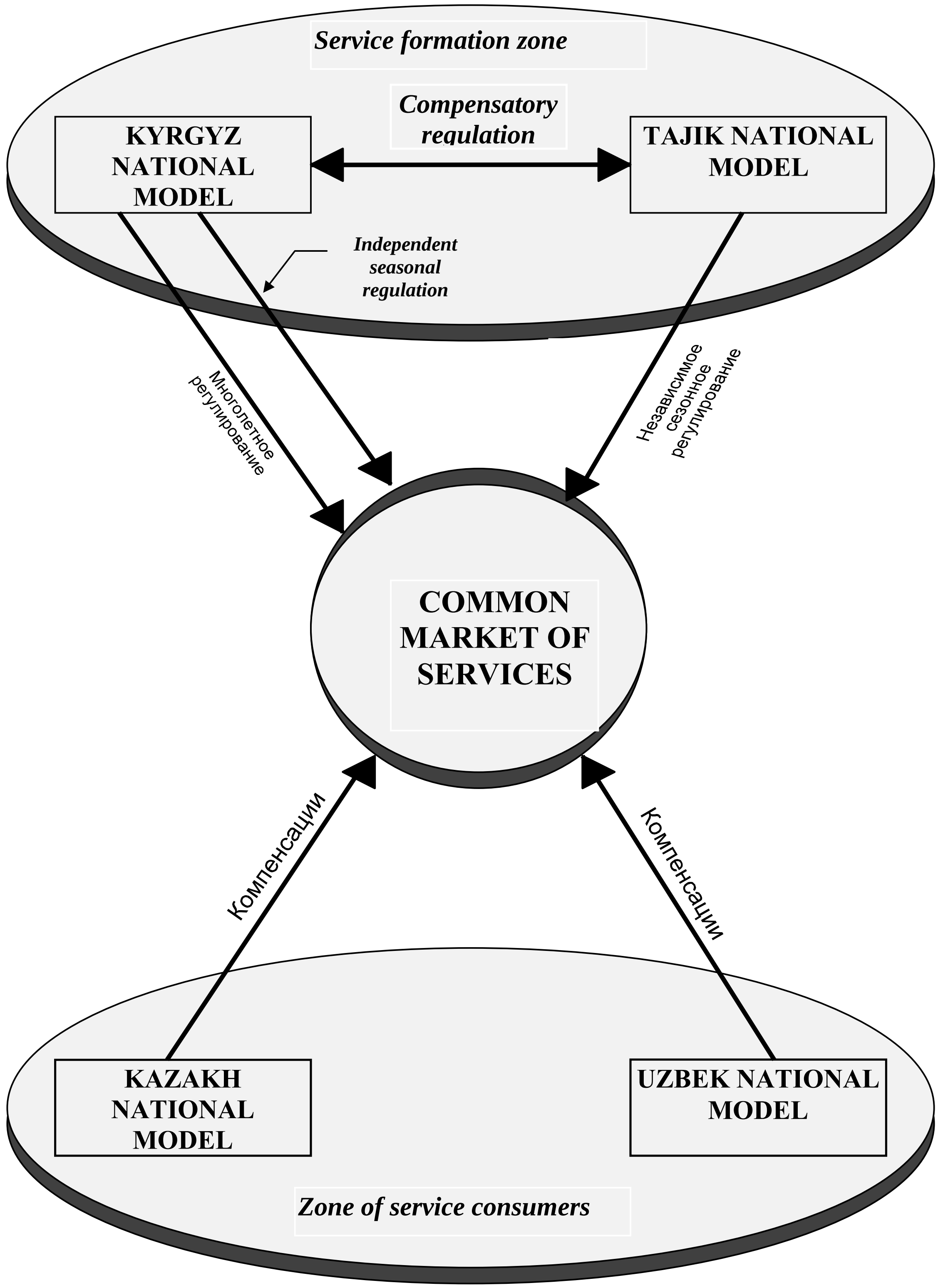
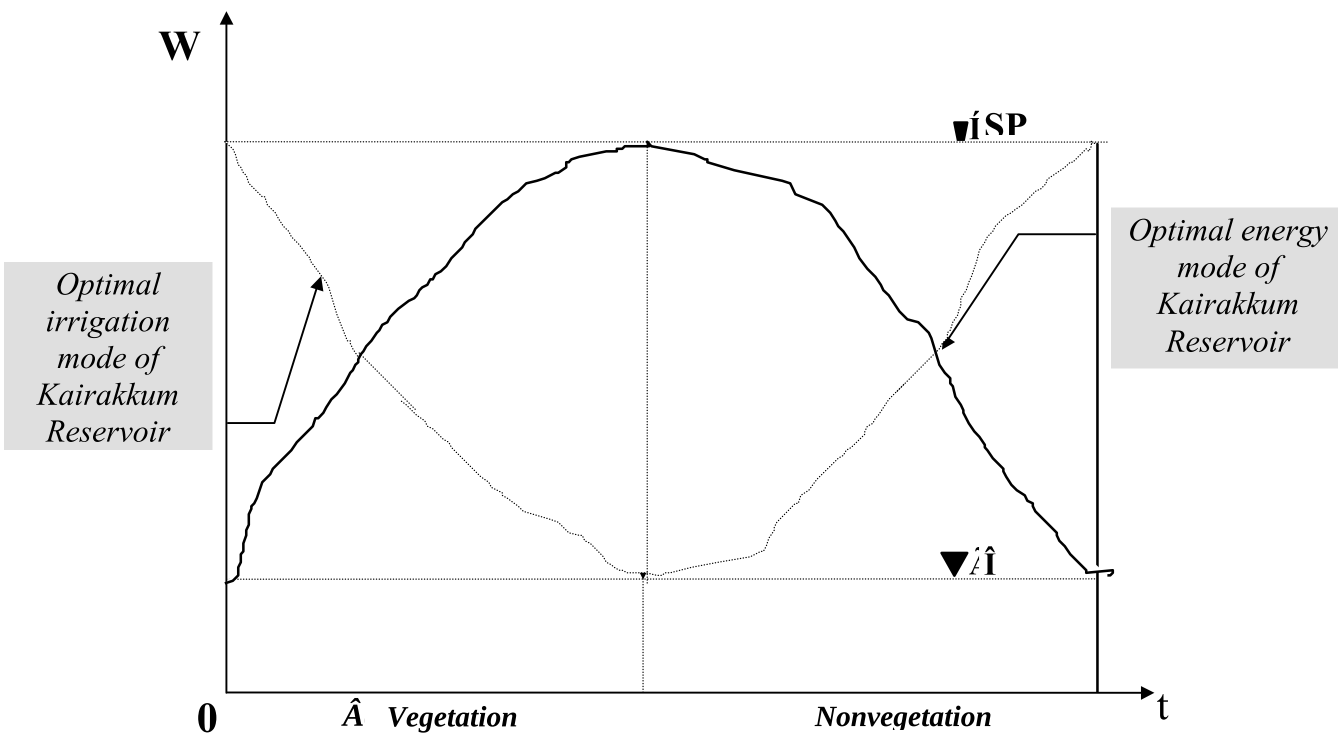


Fig.1. Design Diagram for the Operation of Kairakkum Reservoir (Tajik National Model)





Regional Model of Optimization of the Syr Darya Water and Energy Uses.



Schematic Diagram for Defining Services on Mode Regulation of Kairakkum Reservoir

2.1 Status and Interaction of the Basin Water and Energy Complexes

2.1.1 Water Management Complex

The current situation of the Syr Darya Basin water and power resources may be assessed only with due regard to all history of the region which includes whole complex of problems: economic, social, demographic and ecological issues, etc.

To state all aspects of this situation is the task almost beyond our strength, especially in the course of the present transition period. So the main objective of this paper is to limit the volume and composition of the presented information to such minimum that would be required and sufficient for solving the major target of the EPIC Program: optimization of the Basin's water and energy resources use at the present stage.

This target is not only of the technical character inasmuch the Basin includes in itself several independent sovereign states with diverse economic strategies of their development, various natural and geographic conditions and traditions, etc.

Under such conditions the optimization scheme (and mathematical model) for the use of the Syr Darya Basin water and power resources should, on the one hand, take into consideration the national interests of all Republics: Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan and, on the other hand, as far as is practicable it shouldn't break the relationships have been already developed between them.

Certain complexities are caused by the geographical separation of the territory under review: limiting it only by the Basin of the Syr Darya River. Especially, it is mostly felt as to the power sector representing the unified system of the Central Asia with quite realistic perspective to access to some other countries in the future.

The pooling within the framework of the uniform model of all industries of all Republics' national economies is practically an insoluble problem. The sole feasible criterion for optimization under such conditions there could be the maximization of the total profit or gross domestic product on the common territory but it will require coordination by all Republics of not only the costs, tariffs, prices and profit rates but also of such indicators as material consumption rates and financial resources expenditure rates, the yield of diverse crops and their composition, and so on. This task is practically unrealizable. But what is the most important – all this is not necessary at all. Such approach, in fact, presupposes rigid planning that is the system proved to be both non-effective and unviable. Under conditions of the market economy which all Central Asian Republic change to, all these problems are being solved almost automatically on the basis of the law of demand and supply.

With due regard to all above-mentioned, the optimization scheme for the water and power resources use may be considerably simplified. Each Republic may independently form its own national optimization scheme and develop the required for this mathematical model. In this case coordination of these national programs will be performed on the market basis: through rendering and payment of the respective services.

To ensure the efficient functioning of the scheme, apart from the market conditions there should be created the respective legal base, first of all, in the form of Interstate Agreements. And such base is actually being under creation. There are in force the Agreements between Kazakhstan, Uzbekistan and Kyrgyzstan in the area of the Syr Darya Basin water and power resources use, and on May 5-6, 1999 in Bishkek at the meeting of the experts of the Executive Committee of the CAEC Interstate Council there were initialed and prepared for their signing at the level of Presidents and Heads of Governments the alterations to the existing Agreements including Tajikistan into the sphere of their activities as well as the Agreement on Parallel Operation of the Electric Power Systems.

In case of such outline, for developing the general optimization scheme and model for the Syr Darya Basin water resources use there are required not general assessment and description of the state-of-the-art in this area but the assessment of situation in each Republic separately. Therewith the common issues will have the character of restrictions.

In the line with this, in this paper such situation description is presented for Tajikistan. Therewith in order to decrease the number of details not touching the essence of the problem, the issues of irrigation, considering its subordinate role, are taken into account only in the form of restrictions – in the form of coordinated water sharing quotas operating conditions for the pumping stations and water intakes.

All things considered, the Kairakkum reservoir operation mode is becoming the gist of the reviewed problem determining all national interests of Tajikistan.

2.1.2 Energy Complex

2.1.3 Use and Interaction of the Basin Water Resources for Irrigation and Energy Needs

The whole history of the Syr Darya Basin development may be provisionally divided into three stages.

The first stage – it is from the prehistoric times to the middle of our century. It is characterized by sustainable demographic situation and by lack of the water resources deficit on the whole territory. The power industry, the hydroelectric power sector included, was in its infancy. The whole system was functioning in the regime of the natural runoff. Construction of the water supply system is primarily associated with the distribution irrigation network. This stage is of no interest for us.

The second stage – it involves the period from the 50s to the 90s of our century. It is characterized by intensive development of the irrigated agriculture, primarily on the most cultivable lands – in the valleys of Kazakhstan and Uzbekistan. Just for these purposes in 1957 the Kairakkum hydraulic system was put into operation having one of the largest, at that time, reservoir.

Upon construction of the Kairakkum reservoir, the whole water management system on the Syr Darya River downstream of it was operated in the irrigation regime with seasonal regulation. The power engineering was of the subordinate character. The low-water year of 1974 may be considered as a typical example of this when in relation to the water deficit for the water complete drawdown from the reservoir the units were disassembled and the HPP was brought to a halt.

In 1974 the Toktogul HPP was commissioned on the Naryn river in Kyrgyzstan with the reservoir storage of 19 km^3, in 1976 the Andizhan reservoir was constructed on the Kara Darya River with the reservoir storage of 1.75 km^3 and as a consequence of it the Syr Darya River became completely regulated, and the water system began its functioning in the over-year regulation regime.

This stage of development is of interest for us because at that time in Kazakhstan and Uzbekistan the system of irrigated agriculture has been practically formed based on the complete use of all available water resources. The usage modes for the water resources of the whole Basin were set considering the needs of this system. Such scheme is functioning up to now. It is developed by the BVO Syrdarya. Thus, it may be completely accepted by us as the national model for the modes optimization for Kazakhstan and Uzbekistan.

This water system being used within the framework of the single state – the USSR - completely secured national interests of Tajikistan as well. As to the water resources it was associated with the fact that the water sharing limit set for Tajikistan was very insignificant as compared with other Republics – in the order of 1.5 – 2.0 billion m^3 per year but this volume was supplied at any annual water availability.

As regards the power engineering it should be noted that in the framework of the former unified state, the isolation of two zones of the Republic of Tajikistan from each other – the Leninabad Oblast referring to the Syr Darya Basin and other part of the Republic referring to the Amu Darya Basin was of no concern. Of some interest was only the purchase-sale balance, and it was always favorable due to the excess summer energy from the Nurek HPP.

The third stage – it is the period since 1991, the year of the USSR dissolution and the year of declaring independence by all Republics earlier involved in the Union, and up to the present.

Formally it is characterized by maintenance of all earlier developed relations between the Republics in the area of the water and power resources use (The Nukus Declaration of the Central Asian States and International Organizations Concerning the Problems of Sustainable Development of the Aral Sea Basin. Nukus. September 20, 1995). But this takes place, to a considerable extent, under market conditions. It was particularly observed in the electric power sector but the market elements begin to gain more active access to the water management sector too. Under conditions of independence of all CAEC states this, in its turn, requires execution of legal documents in the form of Agreements, Treaties, etc. And certain work in this direction is also being carried out.

At this stage for the first time the regime for the water and power resources use traditionally being set based upon the interests of more developed in respect of agriculture Republics – Kazakhstan and Uzbekistan is no longer in line with the national interests of Tajikistan. This refers only to the electric power sector. With regard to the water management sector, no problems arise as it was earlier.

In respect of the electric power interests of Tajikistan, the situation is as follows. After separation of the Republics earlier constituting the USSR, there has ceased its functioning the previously existing scheme of the electric power exchange when the electric power generated in summer by the Nurek HPP and being the excess one for Tajikistan was transferred to other Republics, first of all, to Kazakhstan and Uzbekistan which in winter, the deficit period for Tajikistan, returned the electric energy. Such scheme required from the part of Uzbekistan and Kazakhstan, the electric power sector of which is based on the thermal power stations, only to arrange the respective schedules for taking these stations out of service for their repair. Now this scheme is broken down. As a consequence, in summer there is no demand for the excess electric energy of the Nurek HPP, and water is discharged through no-load releases. At the same time the Kairakkum reservoir, precisely at this season of the year, operating with the maximum capacity generates the largest electric energy output. While in winter, the most deficit period for Tajikistan, the Kairakkum reservoir operates with minimum capacity. By that period the water from the Nurek reservoir is also evacuated. As a result, Tajikistan in winter is forced to buy the electric power in the volume approximately of 300 million kWh from other Republics: Turkmenistan and Uzbekistan on unfavorable for Tajikistan terms.

Taking into consideration that the “North” of Tajikistan goes hand in hand with the “South” and 85% of electric energy it receives from the “South”, at present the Kairakkum reservoir operation in such regime is simply unprofitable.

In recent years the drawdown by Kyrgyzstan of the winter component mitigates this situation to a certain extent. But apart from the fact that this will cover the future irrigation in Kazakhstan and Uzbekistan, such approach is simply a temporary one. And this approach will exhaust its potentialities practically after one low-water year.

The scheme of the water and power resources use was developed by the Ministry of Water Management and Ministry of Power Industry of the USSR in the course of many years, stage by stage, depending upon the situation development in the Basin.

In 1940-1945 in the framework of the design statement there were developed the technical design of the Kairakkum reservoir and the plan of the use of the middle course of the Syr Darya River for the power generation purpose.

In 1952 the Design Institute *Sredazgiprovodkhlopok* developed the scheme “Water and Land Resources Use in the Syr Darya Basin” and the Institute *Sredazgidroproekt* developed technical and economic documentation “Hydraulic Power Engineering Estimates to the Scheme”.

In 1953 the Institute *Sredasgidroproekt* developed the “Multipurpose Project for the Syr Darya River”.

In all these projects the flow regulation of the Syr Darya River was specified only by the Kairakkum reservoir. Therewith the irrigation sector was determined as the priority one. The irrigation water demands were specified with allowance made for the irrigation of 474 thous. hectares in the middle course of the River and 160 thous. hectares in the downstream as well as for irrigation and watering of the pasture lands on the total area of 2,430 hectares in the downstream of the Syr Darya River.

The demands of the electric power engineering involved only the observance of the water discharges and water heads rates ensuring the designed discharges and water heads, the installed capacity of the HPP at 126 MW and the firm capacity at 55 MW.

In 1970 the *Sredazgiprovodkhlopok* developed "The Scheme for the Multipurpose Use and Preservation of the Syr Darya Water Resources" and in 1979-1982 the "Refinement of the Scheme for Multipurpose Use …" was prepared by this Institute.

From 1957 to the 80s apart from the Kairakkum reservoir in the Syr Darya Basin there were constructed: the Chardara reservoir on the Syr Darya River, the Charvak reservoir on the Chirchik River, the Andizhan reservoir on the Kara Darya River and the Toktogul reservoir on the Naryn River. As a consequence, the complete flow regulation was ensured and full depletion of the water resources was found by the end of the 80s.

Considering these changes, in 1985 the *Sredazgiprovodkhlopok* developed "The Regulations for the Naryn-Syr Darya Reservoirs Cascade Operation", and in 1986 –
"The Irrigation Demands as to the Flow Regulation in the Toktogul Reservoir During the Transition Period and in the Time of Normal Operation". And finally, in 1987 the *Sredazgiprovodkhlopok* drew up "The Plan of the Water Management Actions in the Syr Darya Basin for the Period of Complete Depletion of the Basin's Water Resources".

In all these documents the irrigation was specified as the major priority, therewith its role was intensifying from year to year. As a consequence, the stipulated in the project rated over-year electric energy generation by the Kairakkum HPP in the amount of 691 GWh was decreased by 1982 up to 522.5 GWh.

This is how matters stand in the project schemes. In actual practice even those minimum requirements that were set in the plans were violated. For example, in the dry year of 1974 the HPP's hydraulic turbines were disassembled for ensuring the complete utilization of the reservoir storage. Although in 1975-1976 the units were not disassembled but for the water complete evacuation from the reservoir the Kairakkum HPP operated in the entirely intolerable operation modes.

In the technological and economic development "The Refinement of Technological and Economic Indicators of the Operating HPPs in the Tajik SSR" drawn up by the *Sredazgidroproekt* in 1988 there was determined the estimated average annual output of the Kairakkum HPP. Considering all requirements of irrigation established in the above-listed documents, it amounts to:

total over the year – 521.7 GWh
including: for the IV-IX period – 371.6 GWh
for the X-III period - 150.1 GWh.

These values well correlate with the actual electric energy output of the Kairakkum HPP over the operation period from 1975 to 1998. It amounts to 528.0 GWh.

The relations between the irrigation and electric power engineering didn't change after 1991 as well except the moment that in accordance with their national interests Kyrgyzstan in the 90s while fulfilling the demands of irrigation in addition to it for the purpose of the electric power sector carried out the drawdown in winter of the over-year component of the Toktogul reservoir.

2.2 National and Regional Interests of the Countries When Using Basin Water and Energy Resources

In the zone of the Syr Darya Basin influence there are situated four Republics of Central Asia: Kazakhstan, Kyrgyzstan, Tajikistan and Uzbekistan. By their national interests regarding the Syr Darya Basin water and power resources use they are divided into two groups.

Kyrgyzstan and partially Tajikistan are situated in the zone of the flow formation and they are interested primarily in the power-purpose use of the Basin water resources. The irrigation for them is of secondary importance. On the contrary, for Kazakhstan and Uzbekistan the irrigation is of primary significance.

The common for all four Republics is the fact that both the interests of the power sector and of irrigation cannot be ensured in the optimal way by the natural and free river flow. It is necessary to regulate the flow as by the seasons so in the regimes of over-year regulation. The major regulating reservoirs in the region are the Toktogul reservoir in Kyrgyzstan with the full storage of 19.1 km^3 and active storage of 14 km^3 and the Kairakkum reservoir in Tajikistan with the full storage of 4.16 km^3 and active storage – 2.6 km^3.

Inasmuch as the flow regulation is practicable only for one of the regimes, it is impossible to satisfy at one time the interests of all four Republics. A certain compromise and coordinated system of compensations are required in such situation.

Under the actual conditions in the region such compromise is feasible provided that the irrigation demands of Kazakhstan and Uzbekistan are satisfied only in case they give compensations to the Republics situated upstream in the form of energy carriers.

As to Kyrgyzstan such scheme of interrelations is in practice since 1995. It is explained, to some extent, by the fact that Kyrgyzstan regularly carries out certain feasibility studies and it is fully resolved to take concrete actions concerning the change of the operation mode of the Toktogul reservoir.

As distinct from Kyrgyzstan, Tajikistan would have to go a long and difficult way to attain only the basic Agreement with other Republics concerning the problem of the Syr Darya Basin water and power resources use considering the role of the Kairakkum reservoir.

On February 2, 1996 Tajikistan proposed to supplement the Draft "Agreement …" between Kyrgyzstan, Kazakhstan and Uzbekistan being already drawn up with the Clauses that take into consideration the interests of Tajikistan (Annex 4). This proposal was merely ignored.

In July of the same year at the Round Table Meeting of the representatives from four Republics Tajikistan made a suggestion on compensating to it the costs spent for operation of the Kairakkum reservoir (Annex 5). But it was not included into the Agreement.

In August 1996 Tajikistan succeeded in inserting into the Protocol of the Experts' Working Meeting (Annex 6) its request to consider a possibility to give it compensations in the form of seasonal transfers of energy.

A fundamental potentiality for considering the interests of Tajikistan was confirmed only at the meeting of experts of four Republics in Almaty in October 1997 when the Draft Agreement was initialed in which the Kairakkum reservoir was specified as an object of regulation having all respective rights. Unfortunately, this Draft Agreement has not been signed.

The results achieved in 1977 were once more confirmed by the experts of four Republics on March 11, 1998 in Bishkek (Annex 7), the Draft "Agreement …" was again initialed, and in this Draft the Tajikistan's rights for compensating the Kairakkum reservoir flow regulation were clearly specified (Article IV).

Unfortunately, this Draft "Agreement …" was drawn up prior to the moment when Tajikistan joined the Interstate Council of four Republics. In view of this, at the Interstate Council Meeting conducted on March 17, 1998 instead of this Draft Agreement there was signed the Agreement considering only the interests of Kazakhstan, Kyrgyzstan and Uzbekistan (Annex 5).

Nevertheless, in April 1999 the Presidents of Tajikistan and Uzbekistan signed lastly the Agreement ensuring compensation to Tajikistan of the services on the Kairakkum reservoir flow regulation in the volume of 150 million kWh. And only on May 7, 1999 the experts of all four CAEC Republics signed the Protocol concerning the introduction of alterations to the "Agreement …" of March 17, 1998 considering in full measure the interests of Tajikistan (Annex 9).

Unfortunately, these agreements on the part of Tajikistan are not substantiated by any estimates. This indicates the urgency of the optimization model for the Syr Darya Basin water and power resources use being now developed under the EPIC Program support.

The major reservoirs in the Syr Darya Basin are the Toktogul reservoir in Kyrgyzstan with the full storage of 19.1 km^3 and the Kairakkum reservoir in Tajikistan with the full storage of 4.16 km^3. These two reservoirs just perform both the seasonal and over-year flow regulation as for the purpose of the power sectors of their own countries so for the irrigation purposes of the Republics situated downstream the River.

Up to now in the Agreements being concluded between the Central Asian Republics based on the suggestions of the BVO Syr Darya it is stipulated that the irrigation regime for the Republics of Kazakhstan and Uzbekistan is ensured by the Toktogul reservoir.

Therewith, taking into account the established by the Agreements between the Kyrgyz Republic on the one hand and the Republics of Kazakhstan and Uzbekistan on the other hand water deficit during the growing season in the volume of 2.0 km^3 is covered at the expense of the flow regulation by reservoirs; the amount of compensations in the course of last three years (1996, 1997 and 1998) was assumed to be constant being equal 2.2 billion kWh per year.

The compensations to the Tajik Party for the flow regulation according to the regimes approved by the BVO are provided but in very limited volumes.

It is presumed that the Kairakkum reservoir performs essentially only the water transit.

Undoubtedly, such situation is not true. According to the world practice, in our case - with the cascade involving two reservoirs for the flow optimal compensating regulation, such regulation should begin at the reservoir situated downstream of the second one. It's clear even from the most general considerations. It is just the lower reservoir that makes the water releases for all downstream water consumers. The upper reservoir may and should be linked up only for the flow regulation in case when the lower reservoir is not able to meet the demands because of its insufficient water storage.

In our case the role of the over-year regulating reservoir remains to belong to the Toktogul reservoir and only to this reservoir. As to the seasonal component, it should be used only as the supplementary one to the Kairakkum reservoir.

At the same time the regulating potentialities of the Kairakkum reservoir are *de facto* applied in full. This is well depicted by the chart of the seasonal elevation changes in the Toktogul and Kairakkum reservoirs given in Figure 1. As it can be seen, taken from the seasonal aspect it is the Kairakkum reservoir that performs the flow basic regulation for the irrigation purposes of Kazakhstan and Uzbekistan. The Kairakkum reservoir, as it is necessary for the irrigation regime, is filled during the nongrowing period and is drawn down during the growing season. The Toktogul reservoir doesn't participate in it, and on frequent occasions it operates even in the opposing regime.

Therewith, Tajikistan underproduces the electric power in winter and incurs severe deficit during this period, as a consequence of it, even in case of grave financial situation in the national electric power system Tajikistan is forced to by electric energy in Turkmenistan and gas in Uzbekistan. The cost of the electric energy purchased by the Republic amounts to 2.5-5.0 American cents per kilowatt-hour. At the same time in summer Tajikistan has a potentiality to generate and export the additional electric power in the volume up to 1.5 billion kWh. But it is closed. Neither Uzbekistan nor Kazakhstan or Kyrgyzstan agree to receive it in such volume under condition if its return in winter. At present the volume of seasonal transfers of energy with these Republics doesn't exceed 200-250 million kWh, and what is more – it is done on discriminatory provisions.

In order to determine the amount of compensations being due to Tajikistan for the flow regulation by the Kairakkum reservoir, let's consider what types of alternative operation modes and flow regulation regimes are, in principle, available for the Kairakkum reservoir.

As one of the most determining implication let it be the provision that the releases from the Kairakkum reservoir in any cases without exception will be made according to the regime set by the BVO Syr Darya for meeting the irrigation demands of Uzbekistan and Kazakhstan. Without going into details, it maybe assumed that the major request arising from this provision involves the necessity in releases from the Kairakkum reservoir during the growing season in the amount of 9 km^3. The rest part of the seasonal flow component should be drawn down during the nongrowing period.

Schematically such diagram of the releases from the Kairakkum reservoir is given in Figure 2 (see the File fizic.xls)- the *Oavs* curve.

One of alternative regimes for the Kairakkum reservoir, let's call it the neutral one, is the regime when the reservoir performs simply the flow transit. It is possible either in case of the reservoir complete drawdown for agricultural development of the reservoir's bed or in case of its change into the lake with the constant elevation of the water surface and practical use of it for fishery and recreation.

In the event of the neutral operation mode at the Kairakkum reservoir, its active storage becomes to be equal to zero and the releases at every instant in time are equal to the inflow volume. So in this version the inflow to the Kairakkum reservoir is described by the same curve *Oabc*. Therewith, the inflow total volume to the Kairakkum over the growing period is determined by the ordinate of the line segment *ab.*

Other alternative operation mode at the Kairakkum reservoir is the irrigation regime, that is practically the one according to which the reservoir operates now. In case of this regime the reservoir is filled by the beginning of the growing season (point *a* in the Figure 2) and it is fully drawn down by the end of this period (point *b*). This will enable to plot for this regime as it is shown in Fig.2 the curve of the emptied reservoir (*debf*) and the curve of the filled reservoir (*заик*). Therewith, the total volume of inflow to the Kairakkum reservoir is determined by the ordinate of the line segment *eb* or, as it's the same, *au*. As compared to the previously considered neutral regime, this volume of inflow determined primarily by the Toktogul reservoir (the lateral inflow and diversions at the reach Toktogul-Kairakkum doesn't depend on the operation mode of the Kairakkum reservoir) is less by the value *ae* (or *bu*) equal to the active storage of the Kairakkum reservoir.

And finally one more operation mode of the Kairakkum reservoir is the electric power regime meeting the national interests of the Republic best of all since it ensures the largest electric power output in winter being the most deficit period. At this regime the reservoir is filled up in summer, the growing season, and is completely drawn down in winter, the nongrowing season. In accordance with this, as it is shown in Fig, 2, the curve of the emptied reservoir will be defined as the broken line *дажf*, and the curve of the filled up reservoir – as the broken line *змbк*. The volume of inflow to the Kairakkum reservoir during the nongrowing season in such case will be equal to the ordinate of the line segment *аж* or to the equal to it ordinate *мb*.This is more than at the neutral regime by the value *ма* (or *bж*) equal to the active volume of the Kairakkum reservoir.

The above-stated analysis indicates that if Tajikistan experiencing acute deficit in the electric power during the winter period changes from the most unfavorable for it irrigation regime of the Kairakkum reservoir to the most optimal for it electric power regime, so Kyrgyzstan for covering the irrigation requirements of Kazakhstan and Uzbekistan in the previous volume shall increase the flow volume by the value equal to the double active storage of the Kairakkum reservoir.

The total active storage of the Kairakkum reservoir now amounts to 2.6 km^3 (dead storage elevation – 340.6 m; active storage elevation – 347.5 m). Thus while changing to the electric power regime of the Kairakkum Reservoir, in order to cover the irrigation needs in the previous volume Kyrgyzstan will be forced to increase the releases' volumes during the growing season by 5.2 km^3.

For the Kairakkum HPP the water-use efficiency in electric power generation is twenty times less than at the Naryn HPPs Cascade in Kyrgyzstan. The "cost" of its transition from the irrigation regime to the electric power one amount to 260 million kWh of electric energy (5.2 km^3 : 20 m^3/kWh). This is that minimum which Tajikistan should receive in any case.

In summary it should be noted again that the whole foregoing analysis refers only to the seasonal regulation of the Syr Darya River flow. As to the over-year regulation, it is, undoubtedly, the hundred-per-cent function of the Toktogul reservoir. Now it may be only speculated how it will be performed and what system of compensations will be in this case. This challenge requires close examination with participation of all parties concerned.

2.3 Major Problems Regarding Interrelationships among/between the Basin Countries in the Area of Joint Use of the Syr Darya Basin Water and Energy Resources

The whole of the Naryn-Syr Darya water and energy structure designed and constructed as if the Central Asian countries were one state. Accordingly, the purpose and operation modes of all facilities including hydropower systems were determined based on one primary criteria, i.e. maximization of the economic benefit for the Central Asian region as a whole, which in its turn was the constituent part of the USSR's economic area.

Two points should be stated. First, the main object in view while developing strategy and tactics of water and energy uses was to gain the maximum benefit. Interests of regions and countries were not taken into account and were often completely ignored. That was one main reason for the economic crisis in all post-soviet area.

Second, the maximum benefit is considered as an achievement of all countries regardless of any concrete input of the republic or branch. From this point of view, it was justifiable to develop irrigated farming on the lower reaches of the rivers, that is in Uzbekistan and Kazakhstan. The damage inflicted upon both water sharing and unhampered fuel and agricultural product deliveries from the adjacent countries compensated energy use of the flow for the up-stream republics (Tajikistan and Kyrgyzstan). Hence, an original compensation mechanism was existing, but it was not a market but a distribution tool.

From today's positions the above pre-independence scheme may be only cognitively and theoretically valuable, as the space changed for taking decisions, both political and economic. Under the conditions of sovereignty for the countries architecting their own economy the criteria of the maximum benefit for the whole of the region can be accepted by none of the countries either in strategic or in tactical aspect.

After the collapse of the USSR and up to nowadays all republics are experiencing the transition difficulties. On the one hand, in order to ensure succession and a smooth transition to the new conditions the Central Asian republics signed the Nukus Declaration on 20 September 1995. There the countries agreed that they all "admit the signed before and operating agreements, treaties and other legislative acts regulating water interelations among and between the Aral Sea basin countries and steadily accept them for implementation". Though it is clear that this is an interim agreement the countries indulge in illusions that former relations may be recovered and strengthened strategically.

On the other hand, market relations start inevitably intruding into water and energy sectors of all republics. In the energy sector, for example, neither power transit nor frequency regulation services are formally and financially executed and consider a supply-to demand matter. Gradually, market relations from the energy sector penetrate into the water sector. The Agreements of 1995-1999 between Kyrgyzstan on one side and Uzbekistan and Kazakhstan on the other side are the typical example of it. The Agreements stipulate mutual compensatory measures in the form of flow regulation by Toktogul Reservoir in exchange of fuel deliveries.

As a result, the existing scheme of interrelationships in the water and energy sector does not meet the interests of any Syr Darya riparian country and at the same time is not optimal for the region on the whole.

Kyrgyzstan being compensated only for the Toktogul seasonal flow control is not interested in an over-year flow regulation and very often it involuntarily releases the reservoir storage intended for an over-year flow regulation, and by this lowers the efficiency of flow use and electricity generation at the hydropower plant.

Tajikistan, establishing the irrigation mode for Kairakkum Reservoir is forced to increase electricity generation at the Kairakkum HPP in summer. And this happens under the conditions of excess energy, waste releases and underloading conditions at the Nurek HPP. All this is done to the detriment of the winter deficit when the Republic buys electricity in other countries at world prices.

Finally, Uzbekistan and Kazakhstan though compensating flow regulation services to Kyrgyzstan do not have any water-supply warranty in the over-year period and very likely do not have extra opportunities to pay for them.

All this illustrates that the existing layout of the Syr Darya water and energy uses is not optimal either in the regional or in the national aspect and requires essential correction.

Under these conditions, the negotiation processes among the basin countries with the aim to find mutual beneficial ways out of the situation are recognized as necessary.

Conflicts in irrigated agriculture between water users of different levels, especially in Central Asia, existed practically all the time. The reasons behind those conflicts were both the shortage of water resources and the difference of interests of individual consumers.

Conflicts as well as other contradictions, as it is well known from dialectics, can be effectively resolved with the help of some third party.

In Soviet times, the government would resolve possible conflicts using command and administrative methods.

Nowadays, due to fundamental changes in the region, the situation became even more complicated. In addition to immanent water management contradictions, which are characteristic for hydroehergy complex, new ones of external nature appeared. This is connected with the fact that nowadays water management and energy systems, built in the past as a single unit for the entire region, have to function within separate states. Besides political factors, the pure effects of scale appeared.

Under these conditions, while resolving conflicts between the individual consumers, economic sectors and, especially, countries, juridical and legal issues come up front.

Of the entire complex of problems connected with the use of water and energy resources of river basins, we shall consider only one, namely, legal aspects of operation regimes of complex-purpose reservoirs (serving irrigation and energy).

The statement of issue itself is therewith connected with contradictions, when interests of the countries-owners, on the territory of which the reservoirs are located, clash with interests of the downstream countries. For example, in the Syr Darya basin major reservoirs, the Toktogul reservoir and the Kairakkum reservoir, are situated on the territory of Kyrgyzstan and Tajikistan respectively. These countries are interested in maximizing electric power generation in winter, the most critical period of the year. The downstream countries, Kazakhstan and Uzbekistan, are contrariwise interested in maximizing irrigation releases in summer, that is in the growing period.

What rights do the countries have therewith and how should the relations between them be built?

In the constitutions of all Central Asian republics, developed based on international standards, there are precise and explicit provisions about it. For instance, Article 13, the Constitution of the Republic of Tajikistan, says: "Land, its subsoil, airspace, animal and vegetal worlds and other natural resources are exclusive property of the state and the state guarantees the efficient use thereof in behalf of the people."

Under our circumstances, this means practically natural law on the necessary operation regimes of reservoirs for the countries owning these reservoirs. Geneva Convention confirms that ([10] Article 7): "Installation and operation of facilities to develop hydroenergy on the territory of each country shall correspond with the laws and regulations used to install and operate such facilities in the country."

It is possible to note that the constitutions contain neither precise identification of waters, that is whether they are internal, international or transboundary, nor specification of any differences between them. At first sight, even the Water Code of the Republic of Tajikistan [2] confirms it. Article 4 of the Water Code states: "In conformity with the Constitution of the Republic of Tajikistan, internal waters of the Republic of Tajikistan are exclusive property of the state. They are national wealth provided only for use. State ownership of interstate (transit) river waters is determined by the agreement of the countries in the river basins."

However, careful analysis of these provisions shows that they refer not to commanding, operation and regimes, but just to property, that is the amounts of water division. Further, the very Water Code of the Republic of Tajikistan confirms it: "Commanding of internal and interstate (transit) water fund on the territory of the Republic of Tajikistan is subject to the state regulation in the area of water relations."

In other words, operation of reservoirs pertains to national states.

Helsinki Rules defines the sense of the use of water resources more specifically [9]. Articles 4 and 5 of these Rules stipulate: "Each country of the basin has the right of reasonable and equal participation in the efficient use of water of the international basin within the territory of the country.

Reasonable and equal participation includes but is not restrained by the following:
e) economic and social needs of each basin country;
f) relative costs of alternative means to satisfy economic and social needs of each basin country;
g) availability of other resources."

Considering in this context the rights of Kyrgyzstan and Tajikistan to use the Toktogul and Kairakkum reservoirs for their energy needs, it is possible to note:

- Under the critical shortage of electric power, especially in winter, the reduction of level of living and termination of the majority of social programs, the energy operation regime of the above reservoirs is just vital;
- The alternative for Kyrgyzstan and Tajikistan may be only the purchased electric power, costing 5-10 times higher than the electric power generated by their own hydropower plants;

- Both Kyrgyzstan and Tajikistan practically have no industrial reserves of energy resources equivalent to electric power.

Thus, in the most general terms of equity, our countries have the right to set operation regimes of reservoirs by themselves, proceeding from their own interests. Moreover, Article 7 of the Helsinki Rules vests this directly and explicitly: "Country of the basin cannot be deprived of the existing reasonable use of waters of international basin in favor of other country of the single basin for the future use of these waters."

Thus, given differences between internal and transboundary waters, at the stage also, international law does not provide any restrictions in respect to the regimes of operation of reservoirs in national interests.

All international standards noted above were developed for "standard", so to speak situations. Under our circumstances, as it is already mentioned, the cardinal demolition of all structures of water management and agriculture, for which they were constructed and operated, took place. It is possible to assume that under these circumstances, due to big sluggishness of these sectors, they cannot avoid feeling certain pressure of previous decisions. In addition, this is actually so.

This is pointed out in Article 1 of the Agreement between four Central Asian republics (without Tajikistan) [3] signed on February 18, 1992 in Almaty, where the equal rights of all countries to use water resources are proclaimed: "Acknowledging community and unity of water resources in the region, the Parties has equal rights to use the water resources and bear responsibility for conservation and protection thereof."

The Nukus Declaration, where all Central Asian countries acknowledge all previously signed treaties and agreements on water resources, points out it more specifically: "We agree that the Central Asian countries acknowledge previously signed and valid agreements, treaties and other normative acts regulating interrelations between the countries regarding water resources in the Aral basin and admit them to be steadily executed."

Formally, this allegedly says about the impossibility for the countries to manage the use of water resources within their territory independently. Signed in the Soviet period, the agreement took into account only the common benefit and strictly regulated the rules managing operation regimes of reservoirs and the single energy system of Central Asia.

Although it is necessary to consider that the prior system provided a system of compensations. For instance, all reservoirs were univocally operated under the irrigation regime for lands mainly of Kazakhstan, Turkmenistan and Uzbekistan. However for that, Kyrgyzstan and Tajikistan carried out unimpeded exchange of electric power with these countries in winter and summer, receiving mineral fuel and agricultural produce.

Yet, agreements, even international ones, are not decrees of nature, which are ever valid. Agreements act in time, they are concluded when the need arises and repudiated when the need passes. This is very precisely stated in the Helsinki rules [9], Article 8: "The existing reasonable use can continue being valid, while the factors justifying the continuation prevail over other factors leading to the conclusion that the use should be modified or terminated to have competing incompatible uses regulated."

Apparently, under the present circumstances there is already no necessity to be guided by resolutions and agreements in water management of the USSR period due to their internal logic. The signing of the Nukus Declaration was caused by the aspiration not to demolish but to smoothly reform the system, not to allow anarchy, but provide the succession of decisions, what is absolutely justified.

Thus, in our specific case, international law does not require the observation of the previous agreements. It is only essential to notify in advance about it. The countries – owners of reservoirs are not restrained in their rights to operate these reservoirs. As a common base of interrelations between the basin countries, it is necessary to develop other acts and agreements complying with the current circumstances. This is pointed out in the Agreement on Joint Actions … signed on March 26, 1993 in Kzyl Orda [5]: "The countries-participants acknowledge the following as common objectives: regulation of the system, improvement of water use discipline in the basin and development of relevant interstate legal and normative acts providing the application of the common regional principles of damages and loss replacement."

In such complicated system as channel basins, it is practically impossible to draw exact boundaries between sectors and their interests. All components are connected with each other too much. Therefore, the principle "do not do any harm" came into being in international relations. This principle is proclaimed in the 4 Parties Agreement of the Central Asian countries signed on February 18, 1992 in Almaty. [3], Article 3: "Each Party participating in the Agreement undertakes to exclude on its territory actions, which concern interests of other Parties and are able to cause the change of the agreed amounts of water consumption and pollution of water sources."

This statement is very tough. It is somewhat explained by the fact that our countries are yet very young and have no sufficient international experience. The statement of the same principle in the Commission on International Law is not so tough …[13], Article 7.1:

"Channel countries shall try to use international channel so as not to cause damage to other channel countries."

But in reality, even in principle, it is impossible to avoid cases, when the activity of some sector, system or object results in the inevitable "damage" for other sectors, systems and objects related to the first. No bans can provide solutions here. Situation may just turn upside-down. Having banned one Party to carry out any activity associated with "damage" for other Party, we just put the first Party before the necessity to damage itself. For instance, having banned Kyrgyzstan to draw down the increased consumption in winter, because this damages Kazakhstan, we make Kyrgyzstan to increase the shortage of electric power during the hardest period.

It turns out that international practice takes this into account. It allows such activity, but only in case of absolute necessity. For this there is the direct instruction of the Commission on International Law [13], Article 7.2:

"If, in spite of exertion, other channel country is considerably damaged, the country, which is guilty in the damage resulting from use, and in case of the absence of agreement on such use, shall start consultations with the aggrieved country regarding:

a) the degree, in which such use proves its equity and reasonableness
b) the issue of use regulation and, if necessary, the issue of damages."

Similar provision is in the Geneva Convention [10], Article 4:

"If contracting country expresses desire to develop electric power, which may cause serious damage to other contracting country, the countries concerned shall start negotiations to conclude an agreement, which will allow such developments to be carried out."

Thus, the factor of influence on other country also does not restrict the activity of countries-owners of reservoirs in their national interests. International law requires only openness, discussing of results and formalization of relations in treaties and agreements.

This general principle is avowedly stated in the Convention on Environment ([8], Article 9.1):

"Riparian Parties conclude bilateral and multilateral agreements or other understandings based on equality and reciprocity in the cases, where there are yet no such agreements, or modify existing agreements or understandings, where it is necessary to eliminate contradictions to the main principles of the Convention …"

Such cooperation should be based on equality and reciprocity ([8], Article 2.6):

"Riparian Parties carry out cooperation based on equality and reciprocity, in particular, by the way of concluding bilateral and multilateral agreements aiming at the working out of concerted policy, programs and strategies, embracing relevant watersheds or parts thereof …" rely on acts of legislation of countries (([7], point iv.4):

"Riparian countries shall concert on coordination and agreeing, as the necessity arises, regarding legislative and administrative measures adopted by the countries in relation to the transboundary internal waters";

be supported by other measures and specific programs ([8], Article 3.1):

"To prevent, restrict and reduce the transboundary impact, the Parties shall develop, approve and implement appropriate legal, administrative, economic, financial and technical measures, and, if possible, achieve their compatibility …"

unconditionally take into account national peculiarities of countries, including national and economic ones ([7], point v.3):

“It is essential to take into consideration existing national and intergovernmental structures and legal provisions, as well as hydrological, ecological, economic and other relevant conditions”;

and provide their obligatory execution ([3], Article 2)

“The contracting Parties undertake to provide strict observation of the agreed procedure and the set rules for the use and protection of water resources.”

All these provisions are very important. Unconditionally, they should be in the agreements. However, economic part is the core and working tool of any agreement. To the purpose, this is directly reflected in international law. Article 13.3, Convention on Environment [8]:

“If some riparian Party is applied by other riparian Party with a request to provide data or information, which are not available, the first Party shall undertake measures to satisfy this request. However, for carrying out the above request this Party can require from the applying Party to pay reasonable costs associated with collection and, if necessary, processing of such information or data.”

If such request relates to information, which is almost neutral in economic terms for the country providing it, the request should be unconditionally extended to services and products of the water and energy sector.

World experience confirms that. The sector of electric power, where market relations took firm stand, is an example.

Consider the problem of electric power transit. This is a good analog of flow regulation concerning transboundary rivers. First, in the Treaty of the Energy Charter there are precisely defined provisions proclaiming free transit. Article 7 of the Charter states:

“Each contracting Party takes necessary measures to facilitate the transit of energy materials and products in conformity with the principle of free transit. Therewith, no differences regarding origin, destination or owner of such energy materials and products and no discriminating tariffs based on such differences, and also no excessive delays, restraints or charges shall take place.

Each contracting Party undertakes to provide transit energy materials and products with the regime no less favorable than that provided for the same materials and products originated from the territory of the Party itself or designated therefor, if only some international agreement does not state otherwise. This is formalized in the provisions of the Party, which regulate the transportation of energy materials and products and the use of facilities for energy transportation.

The contracting Party, through the territory of which the transit of energy materials and products is carried out, shall not cancel or reduce the existing flow of energy materials or products in case of any dispute associated with the transit, before the completion of dispute settling procedure. Equally, the contracting Party shall not allow any subject under control of the Party to cancel or reduce the existing flow of energy materials or products in case of any dispute associated with the transit, before the completion of dispute settling procedure.”

In their specific activity countries confirm this provision in concrete agreements. In particular, the quadrilateral agreement of the Central Asian countries ([11], Article 5) says:

“Parties shall not impede the transit transfer of electric power into third country through their power networks.”

However, the most important is that the practical realization of the agreement is carried out based on specific agreements precisely stipulating economic relations – amount, prices and sanctions of services.

There are the same relations regarding services of power frequency regulation. Gradually, this scheme, taking into account market relations, begins to percolate into the water and energy sector. The principle of compensation between countries in the sector is reflected in the Agreement on the Use of Water and Energy Resources of the Syr Darya Basin [6]:

“Additional electric power generated by the Naryn-Syr Darya cascade of hydropower plants and associated with the release regime of the growing season and multi-year flow regulation in the Toktogul and Kairakkum reservoirs, exceeding the needs of the Kyrgyz Republic and the Republic of Tajikistan, is transferred to the Republic of Kazakhstan and the Republic of Uzbekistan equally.

The compensation for the electric power is carried out through the supplies of equivalent amount of energy resources (coal, gas, fuel oil, electric power) and other products (work, services) or in terms of money as agreed, to the Kyrgyz Republic, to create necessary annual and multi-year reserves of water in reservoirs for irrigation needs.
Carrying out mutual offsets, single tariff policy for all types of energy resources and their transportation shall be provided.”

In summary, we can come to conclusion, that according to all known sources, international law in no way restrain the right of countries to use reservoirs located within their territory in their national interests.

Eventually, given the above, we can formulate the main principle defining the rights of countries to use water and energy resources and their relations with each other as follows:

Any country has the unconditional right to establish any regime for a reservoir owned by the country consistent with national interests.
In the event, if the regime affects interests of other basin countries, the country-owner of the reservoir shall modify the operation regime of the reservoir as agreed, with being provided with corresponding compensations.

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3.2 Operating Models to Manage Basin Water and Energy Systems and Their Assessment from the Point of Optimization of Water and Energy Uses

3.2.1 Underlying Principles of River Flow Complex Regulation

Optimal water management of cascade reservoirs is an objective subject to random effects of the dynamic system with phase and operation variables affected by a complex set of constraints. The problem of optimal water management is very difficult in terms of obtaining a decision by analytical and numerical methods. Moreover, obtaining a decision by these methods is time consuming and requires big computer memory.

In this situation, analytical optimization models for the management of the cascade of reservoirs are of great interest. In this work there were considered two groups of analytical models for managing cascade of reservoirs.

The first group has an objective to maximize water storage of a single reservoir, as well as storage of the whole cascade of reservoirs, under the constraints of total power production. Let us consider, for example, the objective of optimal management of two reservoirs under the constraints of total power production. The objective can be represented in the following way:

1. $x_1(T) + x_2(T) \Rightarrow \max\limits_{u_1(t),\, u_2(t)}$

2. under the following constraints:

$$\begin{cases} \dfrac{dx_1}{dt} = v_1 - u_1, \\ \dfrac{dx_2}{dt} = u_1 - u_2, \end{cases}$$

3. $u_i \in U_i = \{u_i^- \le u_i \le u_i^+\}, i = 1,2.$

4. $\int_0^T (x_1 u_1 + x_2 u_2) dt \ge E^*, E^* = const,$

5. $x_1(0) = x_i^0, i = 1,2.$

where $x_1(t)$ is the volume of the first reservoir at the point *t;*
$u_1(t)$ is a release from the reservoir *i* at the point *t* ($v_i(t) \ge 0$);
E* is a total power generation demand from two power stations;
and t (0,T) is time equal to one year.

The equations 1-5 are referred to equations of optimal management with mixed constraints of integral nature where Lagranzh principle is used.

Without referring to complicated technicalities it can be noted that through some simplifying assumptions it was proved that the optimal management for equations 1-5 is expressed as follows:

$$u_1^*(t) = \begin{cases} u_1^-, 0 \le t, < t_1^* \\ u_1^+, t_1^* \le t \le T \end{cases}$$

6. $$u_2^*(t) = \begin{cases} u_2^-, 0 \le t < t_2^* \\ u_2^+, t_2^* \le t \le T \end{cases}$$

Then, **theorem 1** is proved. *The moment of switching of the first reservoir occurs earlier than the moment of switching of the second reservoir, i.e.:*

$$t_1^* \le t_2^*.$$

One of the main qualitative results reached after considering the functioning of two reservoirs located one after another is connected with the fact that the optimal management is close to the boundary points, i.e., $u_1 \in [u_1^-, u_i^+], i = 1,2$.

Thus, under the condition of maximizing water storage of reservoirs and constraints connected with the total power generation, the drawdown of reservoirs srarts from the one located upstream. This fact serves as a heuristic basis for regulating hydro nodes which is a main element in designing water management systems.

The second group of models is dedicated to qualitative study of the objective of maximizing the total guaranteed power capacities of the cascade hydropower stations. The results of the study provide a basis for one of the rules widely used in practice, i.e., *drawdown of reservoir capacities must start from upstream ones first and then proceed downstream in order to meet energy demands.*

Balance relationships lie in the basis of the model. Each reservoir initial water storage is assumed to be specified and used during the specified period of time with no inflows. The capacity developed by each hydropower station of the cascade is assumed to be as proportionate to multiplication of water flow through turbine on the water head, which, in turn, is taken as being proportionate to the volume of the reservoir (i.e., the level of the lower reach is considered to be constant). These assumptions are quite natural for mountain reservoirs in winter periods. Parameters for managing are connected with releases and water flow through turbines of hydropower stations of the cascade at each moment of time. The objective of the management is to maximize the implementation of the power capacity schedule.

We have the following optimal management objective:

7-14

$$
\begin{aligned}
&\beta = \max, \\
&\frac{dx_1(t)}{dt} = -u_1(t), t \in [0, T], \\
&\frac{\mathrm{d}x_1(t)}{dt} = u_{i-1}(t) - u_1(t), i = 2, \ldots, n, t \in [0, T], \\
&\sum_{i=1}^{n} k_i x_i(t) u_1(t) \geq \beta \mathrm{N}(t), t \in [0, T], \\
&u_1(t) \geq 0, i = 1, \ldots, n \\
&x_1(t) \geq x_i^-, i = 1, \ldots, n, t \in [0, T], \\
&x_1(T) \geq x_i^T, i = 1, \ldots, n, \\
&x_1(0) = x_i^0, i = 1, \ldots, n.
\end{aligned}
$$

where x_1 is the volume of the reservoir *i* (the numbering starts from the upsream reservoir and then go downstream)**,** u_i - is a release from the reservoir *i;* N(t) – is a schedule of the required total power capacity; β - the level of implementation of the schedule; κ_i - proportionality factor of the power capacity of hydro power station *i*; x_i^- - volume of water in the reservoir i adequate to dead storage; x_i^T - water storage of reservoirs necessary for satisfying irrigation demand; x_i^0 - initial water storage of the reservoir *i*. It is assumed that $0 < x_i^- \le x_i^T \le x_i^0$, where $i = 1,\ldots,n$.

The equations 7-14 represent the objective of optimal management with mixed constraints. Though, equation optimal conditions, like Ponrtyagin maximum principle, are known for these equations, they do not provide with a concrete solution. However, in this case we managed to receive a concrete analytical solution.

We have the following optimal equation:

$$u_i^0(t,x_1,\ldots,x_n) = \begin{cases} 0, when x_i \le x_i^T or \sum_{j=1}^{i-1} x_j > y_{i-1}^T, \\ \beta^0 N(t) / k_i x_i, otherwise \end{cases}$$

$$where \beta^0 = P / E, E = \int_0^T N(t)dt,$$

$$P = \sum_{i=1}^{n} k_i (\int_{x_i^t}^{x_i^0} x dx + \int_{y_{i-1}}^{y_{i-1}^0} (y_i^0 - y) dy),$$

$$y_i^* = \sum_{j=1}^{i} x_i^0, y_i^T = \sum_{j=1}^{T} x_i^T, i = 1,\ldots,n, y_0^0 = y_0^T = 0.$$

Thus, $\bar{u}^0 = (u_1^0(t),\ldots,u_n^0(t)), \bar{x}^0(t) = (x_1^0(t),\ldots,\chi_n^0(t))$ are trajectories obtained through synthesis $\{u_i^0(t,x_1,\ldots,x_n)\}$ instead of **u** in the equations 8-9. Under the condition (14) **theorem 2** is correct. The expression $\beta^0, \bar{u}^0(t), \bar{x}^0(t)$ is an optimal solution to the equations 7-14.

It should be noted that drawdown of each reservoir, according to optimum synthesis definition $\bar{u}^0(t,x_1,\ldots,x_n)$, starts when all the upstream reservoirs are used completely.

Note: For purposes of simplifying the notations it was assumed that the structure of the cascade is linear. Theorem 2 is also accurate for any treelike cascade.

At the conclusion it must be noted that in case of the first group of models it was assumed that energy demands are satisfied first, then irrigation demands. The second group, vice-versa, implies that energy demands are satisfied with the water left after irrigation. But in both cases it turns out that it is more advantageous to start drawdown from the upstream reservoirs and then proceed downstream.

3.2.1.2 Optimization Scheme of the Use of Water and Energy Resources in the Syr Darya Basin

The problem under consideration is a complex problem. Its settlement is possible only upon simultaneous consideration of all issues: legal, economic, managerial, organizational, and mathematical.

The main goal of the proposed complex optimization model is the most effective use of all water-energy resources of the basin of Syrdarya river through mutual coordination of the national interests of separate republics.

The Scheme of the Seasonal Optimization Model

Step 1. Establishment of the rights and obligations for the Central Asian Economic Community countries, as well as of the basic principles of relationships between them in the sphere of the use of the water-energy resources of the basins of the transbordering rivers.[1)]

Step 2. Development and coordination of an annual forecast of the estimated water resources of the Syrdarya river.[2)]

Step 3. Optimization of the use of the water-energy resources in the Kyrgyz Republic.[3)]

Step 4. Optimization of the use of the water-energy resources in the Republic of Tadzhikistan.[4)]

Step 5. Establishment of an optimal regime of water consumption in the Republic of Kazakstan.[5)]

Step 6. Establishment of an optimal regime of water consumption in the Republic of Uzbekistan.[6)]

Step 7. Coordination of the regimes of water consumption in the Republic of Kazakstan and the Republic of Uzbekistan. Determination of a common regime of water consumption at the border between the supply zone (Kyrgyzstan + Tadzhikistan) and the consumption zone (Kazakstan + Uzbekistan).[7)]

Step 8. Comparative analysis of the regimes of water supply and demand at the border between the zones. Determination of the deficit of demand during the vegetation period. Development of proposals on how to cover the deficit of demand and of the mechanism of compensation.[8)]

Step 9. Conclusion of annual agreements between the four republics of the basin with establishment of concrete amounts of services on drainage regulation, reception and return of power and other energy sources.[9)]

Step 10. Correction of **step 4**, and, if necessary, of **step 5** in order to guarantee the regime established within **step 7**.[10)]

<u>Step 11.</u> Providence of implementation of the regimes of water drainage within the basin established within the previous steps. Management of water divisions.[11)]

<u>Step 12.</u> Providence of the most effective fulfillment of the agreements on the flows of power executed within **<u>step 9</u>**. Management of power divisions.[12)]

<u>Step 13.</u> Monthly correcting of the forecast of the estimated water resources of the Syrdarya river basin.[13)]

<u>Step 14.</u> Return to the 3rd and all the following steps in order to correct them on the basis of the clarified prognosis of drainage.[14)]

The above scheme of the seasonal optimization model is presented in Figure 1.

The Scheme of the Long-term Optimization Model

This section considers only several basic approaches to the long-term optimization model. Its detailed development is a separate issue.

Commonly, the basic mechanism of long-term control of drainage unclearly appears in the above seasonal model. It is the scheme of surplus collection and coverage of deficit by the Toktogul water reservoir*, appearing in the **14th step**. Of course, the elements of long-term control can be accounted for in **steps 3-7**.

Unfortunately, yet it is not set anywhere to be a service provided by Kyrgyzstan, which requires corresponding compensation. As a result, Kyrgyzstan, when fulfilling its obligations towards the downstream parties, in relation to the regime of vegetation period, is almost not interested in fulfilling any conditions related to long-term control during the between-vegetation period.

That is why it is necessary to develop and set by international agreements the basic principles guaranteeing long-term control of drainage at the Toktogul water reservoir for the interests of all countries of the Central Asian Region.

The next step shall be the determination of the price of services for long-term control and of the payment mechanism. It is suggested that, unlike under the seasonal model, under this model the payment shall be carried out not upon the fact and during provision of the control services, but shall be long-term. Otherwise, the countries mostly interested in long-term control of drainage will be required to bear costs during the most hard arid years.

* Long-term control of drainage can be carried out only at the Toktogul water resrvoir.

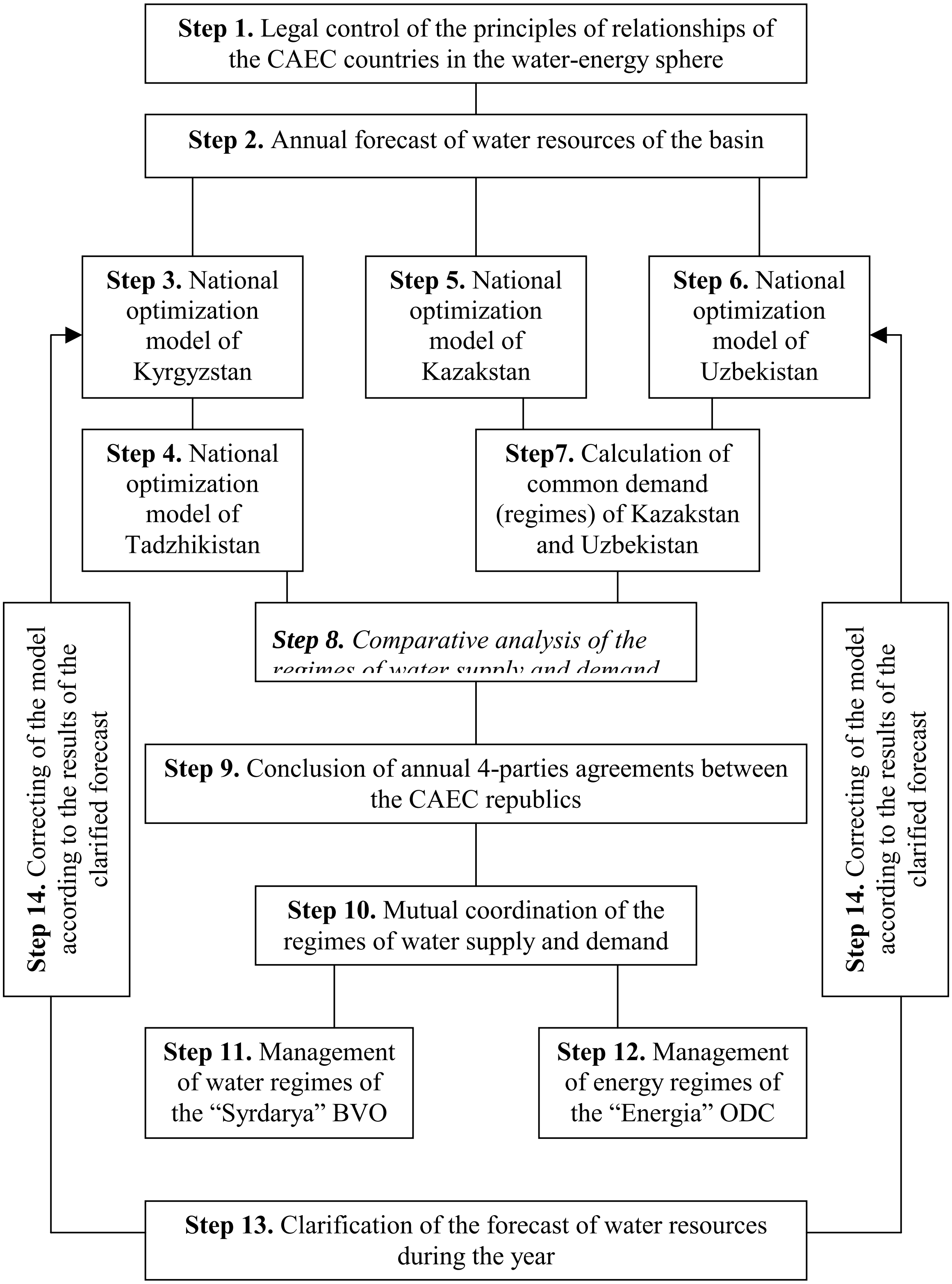


Figure 1. Scheme of the seasonal optimization model.

Notes.

1. The issue of rights and obligations of separate states regarding the establishment of the operation regimes of the water reservoirs allocated within their territories is the most important and crucial issue. The option proposed by the Tadzhik party is presented in the material transferred to EPIC [1].

The general principles of relationships between the republics on the base of mutual compensations are set by Article IV "Agreements between the Government of the Republic of Kazakstan, the Government of the Kyrgyz Republic, the Government of the Republic of Tadzhikistan, and the Government of the Republic of Uzbekistan on the use of the water-energy resources of the basin of the Syrdarya river" developed with the support of the US Agency for International Development (USAID) and the Executive Committees of the Interstate Council of the CAEC republics, and initialized in the city of Bishkek on March 11, 1998.

2. The forecast shall be developed by the beginning of the year for the whole period (12 months), and shall be further clarified monthly. It shall be carried out by BVO "Syrdarya".

3. It shall be carried out with the use of the optimization mathematical model analogous to the one developed for Tadzhikistan [2, 8].

The optimization criterion – guaranteeing of the necessary (set) amount of power generation (or its maximization) during the winter – the most deficit – period of the year.

The genral initial data – forecast of the inflows to the Toktogul water reservoir.

The result of optimization – the operation regime of the Toktogul water reservoir guaranteeing the national interests of Kyrgyzstan.

4. A national optimization mathematical model of operation of the Kairakkum water reservoir shall be developed (on the basis of GAMS language) [2, 8].

The optimization criterion – maximization of power generation by the Kairakkum HPP during the deficit between-vegetation period (without any conditions during the remaining period of the year).

The general initial data – inflows to the Kairakkum water reservoir: the regime of outflows from the Toktogul water reservoir, adjusted by the forecast of integral inflow and taking out between the Toktogul and the Kairakkum water reservoirs.

Limitations – irrigation requirements.

The result of optimization – the operation regime of the Kairakkum water reservoir guaranteeing the national interests of Tadzhikistan.

5. Shall be determined under the currently existing methodology of the BVO “Syrdarya”, or on the basis of the planning zones model.

The general initial data and limitations – the forecast of water resources of the basin of Syrdarya river with the account for the set principles of water distribution between the CAEC republics.

The result – determination of the optimal schedule of water consumption with the account for the national interests of Kazakstan.

6. Shall be carried out analogously to **Step 5**.

The result – determination of the optimal schedule of water consumption with the account for the international interests of Uzbekistan.

7. Shall be determined by simple summarizing of the schedules of water consumption of the Republic of Kazakstan and Uzbekistan. It can be noted that **Steps 5, 6 and 7**, actually, are the activities currently carried out by the BVO “Syrdarya” when developing common regimes.

8. The regime of common water consumption for Uzbekistan and Kazakstan shall be set directly for the range on the border with Tadzhikistan.

The water supply regime shall be determined by the adjustment of the regime of outflows of water from the Kairakkum water reservoir by the integral amount of the side inflow – taking out water from the river between the Kairakkum water reservoir and the border with Uzbekistan.

The deficit of demand for water during the vegetation period for Uzbekistan and Kazakstan shall be determined by simple summarizing of the above schedules.

Coverage of the deficit of water for Kazakstan and Uzbekistan during the vegetation period is possible only through corresponding changes in the regime of outflow in the supply zone. Two options are available in this context. Under the first option, the Kairakkum water reservoir shall operate in its optimal energy regime as determined at **Step 4**, and the whole necessary amount of water shall be delivered additionally from the Togtogul water reservoir.

Under the second option, the general seasonal operation shall be carried out by the Kairakkum water reservoir, while the Toktogul water reservoir shall be used only in case if the operated volume of the Kairakkum water reservoir appears to be insufficient.

The second option is more effective in all contexts:

- The cost of outflow regulation services **“water ⇔ power”** at the Kairakkum water reservoir is lower than at the Toktogul water reservoir, and the necessary and paid for amount of outflow provided during the vegetation period from the Toktogul water reservoir increases upon transfer from the second option to the first option by the amount equal to the double useful volume of the Kairakkum water reservoir, that is 5.2 billion m^3.

- Under the second option, the Toktogul water reservoir becomes free from seasonal regulation, and it can more effectively than now fulfill its main function – long-term outflow regulation.

Such an approach is commonly known. It is presented in all manuals on outflow regulation and even has a special name – **"compensating regulation"**.

As a mechanism of compensation of outflow regulation services provided Uzbekistan and Kazakstan by Kyrgyzstan and Tadzhikistan, the most simple and rational is the presented in the 4 parties agreement (Point 1 of the Notes) and existing during 5 years mechanism between Kyrgyzstan from the one hand, and Kazakstan and Uzbekistan on the other hand, under which the equivalent of water and hydraulic power generated with its use is established. While this, the republics receiving water during the vegetation period also receive the power generated with its use, and return the latter (or other equal energy) during the between-vegetation period.

9. Such agreements can be analogous to the currently existing during the last 4 years agreements between Kyrgyzstan, Kazakstan and Uzbekistan, but with he participation in the activities of the fourth party – Tadzhikistan.

10. It shall be provided with elementary calculations.

11. It shall be carried out with the use of the programs or models developed by the BVO "Syrdarya".

12. It shall be carried out with the use of the programs or models developed by the ODC "Energia".

13. It shall be carried out by the BVO "Energia".

14. Such adjustment shall not be just a repeat of **Steps 3-13** on the basis of the new forecast for the remaining period of the year. Existence of the Toktogul and Kairakkum water reservoirs allows to use them as the buffers for "**correcting**" the activities carried out earlier. It shall be carried out as the following. The Kairakkum water reservoir before the clarification of the prognosis shall have outflows under the regime set earlier, regardless the inflows to it. In case if the actual inflows to it are higher than the expected and the water reservoir is overloaded in comparison to the set level, then during the next stage the excess shall be decreased by means of the decreases in the outflows from the Toktogul water reservoir. And vice versa, if the inflow to the Kairakkum water reservoir is lower than the calculated one, then the Toktogul water reservoir shall cover it during the next stage.

3.3 GAMS Code as an Instrument for Building Complex Optimization High-Level Models

GAMS is the English abbreviation of the *General Algebraic Modelling System.* This technology has been created for compact representation in the form of mathematical models of processes surrounding us. A large composition of well-known methods (linear, non-linear, integer-valued and others) of mathematical programming form the GAMS mathematical basis.

The modelers write that GAMS was put up as a means:

- To ensure a high level of the language for compact represntation of big and complex models;
- To allow doing overpatching relatively fast and safe;
- To present single-valued operators of algebraic connectivits in simple forms;
- To allow describing the model that would not depend upon the solution algorithm.

Meantime it is known that testing, with simple problems taken as an example, is necessary to do justice to any algorithmic computer language. As in the GAMS system various mathematical methods of optimization are laid (in the form of different "solve" matters), then, the aspiration of the first users (the Technical Group members) to estimate "good behavior" of the system solving simple problems was evident.

On this basis we used test examples and two directions to try the GAMS code:

Use of the GAMS Technology to Solve Linear and Nonlinear Problems of Mathematical Programming

1. Integer-Valued Linear Problem

1.1. Problem Definition. An Integer-Valued Linear Problem (ILP) is a Linear Problem (LP) in which some (and likely all) variables should have integral values.
The ILP may be formulated as follows:
It is necessary to find maximum of function

$$F = \sum_{i=1}^{n} c_i x_i \qquad (1)$$

on condition that

$$\sum_{j=1}^{n} a_{ij} x_j = b_i \qquad (i=1,2,...,m), \qquad (2)$$

$$x_j \geq 0 \qquad (j=1,2,...,n), \qquad (3)$$

$$x_j \text{ - integer} \qquad (j=1,2,...,n), \qquad (4)$$

To find optimal solutions for (1)-(4) special methods are required. One of the most familiar methods is the Gomori method, based on the dual simplex method. Consider a specific example.

Example 1. It is necessary to find the maximum value of the function

$$F = 7x_1 + x_2 \qquad (5)$$

If to perform the conditions:

$$\begin{cases} 9x_1 + 4x_2 + x_3 = 110 \\ 11x_1 - 3x_2 - x_4 = 24 \\ 2x_1 - 7x_2 - x_5 = 15 \end{cases} \qquad (6)$$

$$x_j >= 0, \quad (j=1,2,...,5) \qquad (7)$$

$$x_j \text{ - integer}, \quad (j=1,2,...,5) \qquad (8)$$

By the way, note that the solution of (5)-(8) by the Gomori method gives the following result: $x_1 = 12$, $x_2 = 0$, $x_3 = 2$, $x_4 = 108$ è $x_5 = 9$. The maximum value of the objective function is F = 84.

Consider the simplest example of the GAMS usage for the solution of (5) – (8). Below are the main model fragments to solve the ILP using the GAMS language:.

```
*** GAMS file for Example Illustration
*** Mixed Integer Linear Program Version
*** Sobir.T. Navruzov
Sets
        i  type of variable            / x1,x2,x3,x4,x5 /
        j  type of constraint equations / equ1, equ2, equ3 / ;

Parameters
          c    coefficients in objective function
             / x1     7.0
               x2     1.0
               x3     0.0
               x4     0.0
               x5     0.0  /

          b  right hand sides of constraint equations
             /equ1     110.0
              equ2     24.0
              equ3     15.0/  ;

Table a(i, j) coefficients in constraint equations

               equ1       equ2       equ3
```

```
   x1          9.0     11.0      2.0
   x2          4.0     -3.0     -7.0
   x3          1.0      0.0      0.0
   x4          0.0     -1.0      0.0
   x5          0.0      0.0     -1.0  ;

Variables
      fun;

INTEGER variables
                        x(i);
Equations
        obj        objective function
        const(j)    constraint equations ;

obj  ..   fun  =e=  sum ( i, c(i)*x(i) )  ;

const(j)  ..   sum(i, a(i,j)*x(i)) =e= b(j) ;

model  exam1MIP / all/ ;
```

solve exam1MIP using MIP maximizing fun;

```
display x.l ;

file res / resultMIP.txt/;
put res;
put "x1=", put   x.l('x1') , put /
put "x2=", put   x.l('x2') , put /
put "x3=", put   x.l('x3') , put /
put "x4=", put   x.l('x4') , put /
put "x5=", put   x.l('x5') , put /
put "objective value",    put   fun.l  ;
```

After the model run we get a result:

x1= 11.00
x2= 1.00
x3= 7.00
x4= 94.00
x5= 0.00
objective value F = 78.00

As we see the solution is not optimal, as an optimal solution maximizes the value of the objective (5), but we have the solution received by the pruning method (Gomori method) **{12;0;2;108;9}** and **F = 84.**

Then, the next important conclusion is that we should not conceive the original solution as optimal unless it is proved.

Application of GAMS for Solving Optimization Problems
(Methods of Model Validation and Sensitivity Study)

Knowledge of algorithms for solving optimization problems is necessary but not sufficient for conducting a successful research. First and foremost, it is necessary to formulate the problem for optimization and make necessary preparations for its solving, select the appropriate algorithm, choose and write down an effective program for implementation of the algorithm, make a number of optimization calculations including various adjustments to the problem and algorithm, and finally, after receiving a reliable solution, interpret it in terms of the real system, and use it in practice.

Thus, the optimization process includes at least three stages:

- **Construction of the model;**
- **Model implementation;**
- **Assesment of the solution.**

We shall follow this scheme in studying optimization problems. However, it should be noted that **the objective of this presentation** is studying the reliability of solutions of optimization problems based on GAMS, i.e. methods of justification of solutions and sensitivity analysis to changes of model parameters.

1. Model Construction

The problem for applying optimization methods must include an efficiency criteria (objective functional), a number of independent variables, and constraints in the form of equations and inequations constituting **the model** of the system under consideration. The description and construction of the model of the real system is the most important stage of optimization, since it defines the practical value of the solution and its implementation.

The optimization process by using the model can be considered as a method of searching for an optimal solution of the real system without direct experimental work with the system itself. As it is shown on Figure 1, the "direct" way for optimal solution is replaced with the *"bypass",* which includes construction and optimization of the model, as well as transformation of the found results into some practical form. Obviously, this approach to system optimization requires a more simplified presentation of the real system. This approximated approach to the formation of the model must include main characteristics of the system to be reflected in the model. It is also necessary to formulate a logical rationale for constraints and choose a form for model representation, as well as the level of its specification and method of implementation using computer technologies. These considerations refer to *the stage of model construction*.

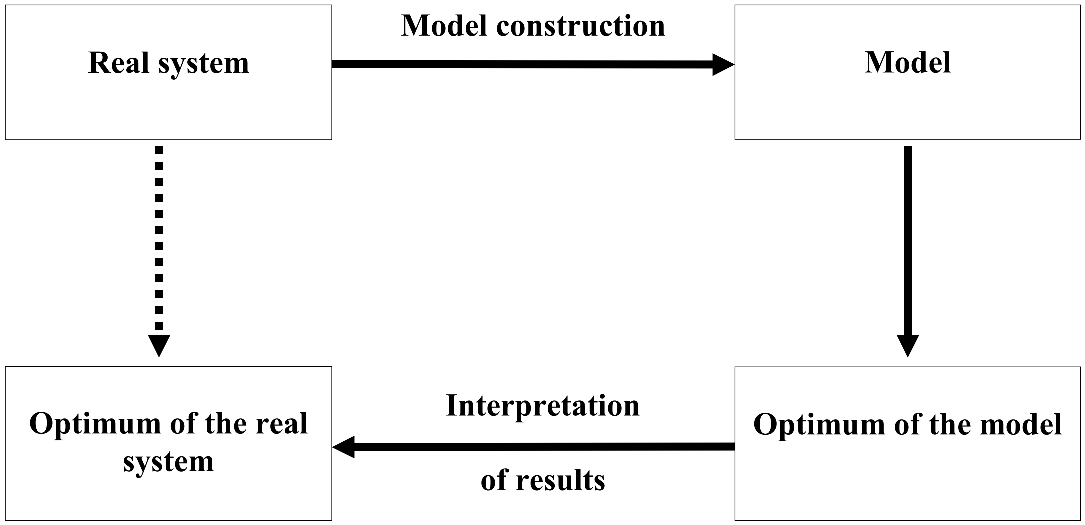


Fig. 1. Application of optimization models.

The quality of the model can be evaluated neither in terms of structure nor form. The only *criteria* for such *evaluations* are associated with *the reliability of model forecasts* of behavior of real systems. Models including non-linear functions could be considered as more preferable than linear models only if non-linear model can provide with a more detailed description of the real situation.

It must be noted that the correspondence of the model to the modeling system could be true only to a certain degree. Since the model itself is just a simplification of real relationships, absolute criteria for ranging of models are non existent. However, a modeler should have a good knowledge of the modeling system, understand technical principles of the model components, and make all the calculations necessary for optimizing a feasible project.

Let us consider some concrete examples of construction of optimization models taking into account the aforementioned scheme of logical relationships referred to the process of model construction.

Model 1.

Consider a problem of planning and management on a farm level, i.e. the problem of allocation of resources. The problems of allocation of resources arise whenever it is necessary to engage in several types of activities that have constraints related to availability of resources or their use. Such cases are characterized by problems of optimal allocation of available resources among users. The majority of these problems can be solved through mathematical programming or other related methods.

In this study we shall concentrate our efforts on problems of allocation of resources where the data used is known and manipulations with the value of farmer can either maximize profits or minimize costs.

Consider the following problem: *A farmer raises two crops X and Y on the area of 160 units. He has to distribute land, human resources and equipment for maximizing the revenues. The process of raising crops implies three components of work: ploughing***, sowing, and harvesting.** *The Table below shows these three operations with periods for their implementation associated with four seasons of the year:*

Season	Actual time (hour)	Required time (hour/units of land)					
		Crop X			Crop Y		
		Plow	Sow	Harvest	Plow	Sow	Harvest
1	5	0,5	-	-	-	-	-
2	10	-	0,3	-	0,5	-	-
3	15	-	-	0,75	-	0,6	-
4	20	-	-	0,75	-	-	2,0

Crop X can be harvested in the time interval of 3 or 4. However, if harvesting requires time interval 4, then the cost is 0.2 hour/units of land.

We now proceed to the **process of construction of the mathematical model** of the problem.

Let us assume that x_3 and x_4 denote land areas for crop X, which is harvested in seasons 3 and 4 accordingly. In addition, we have land area for crop Y.

- Land area for each crop is restricted by total available land:

$$x_3 + x_4 + y <= 160 \qquad (1.1)$$

- For harvesting each crop a combine is used. Assume that ρ_n is a number of harvesters required. The number ρ_n must be integer and non-negative (0,1,2,3, etc.). Thus, we have three constraints:

$$\text{Season 3: } 0{,}75x_3 <= 15p_n\ ; \qquad (1.2)$$

$$\text{Season 4: } 0{,}75x_4 + 2{,}0y <= 20p_n. \qquad (1.3)$$

- A tractor is required for ploughing and sowing. During harvesting, a tractor and a combine harvester is required. If ρ_t is an integer non-negative value for tractors, then:

$$\text{Season 1: } 0{,}5(x_3 + x_4) <= 5\rho_t; \qquad (1.4)$$

$$\text{Season 2: } 0{,}3(x_3 + x_4) + 0{,}5y <= 10\rho_t; \qquad (1.5)$$

$$\text{Season 3: } 0{,}75x_3 + 0{,}6y <= 15\rho_t; \qquad (1.6)$$

$$\text{Season 4: } 0{,}75x_4 + 2{,}0y <= 20\rho_t \qquad (1.7)$$

Requirements for labor resources are evaluated in the following way. One tractor operator is required for ploughing and sowing. For harvesting crop X, two persons are required for operating combine harvesters and one for operating a tractor. One tractor operator and one combine operator are needed for harvesting crop Y.

- If ρ_m is an integer variable denoting labor resources demand, then labor constraints (man/hours) can be represented in the following way:

Season 1: $0,5(x_3 + x_4) <= \rho_m;$ (1.8)

Season 2: $0,3(x_3 + x_4) + 0,5y <= 10\rho_m;$ (1.9)

Season 3: $3*0,75x_3 + 0,6y <= 15\rho_m;$ (1.10)

Season 4: $3*0,75x_4 + 2*2,0y <= 20\rho_m;$ (1.11)

Crop Y can be raised on one and the same field only one year in the time interval of two years, while crop X – two years in the time interval of three years. If a farmer wants to raise this crop every year, rotation of crops must be used.

- It can be formulated considering constraints:

$Y <= 160/2;$ (1.12)

$x_3 + x_4 <= (2/3)*160$ (1.13)

- Revenues from each crop X and Y are equal to 2 and 4 units/units of land. Respective annual requirements for labor, harvesters, and tractors are equal to 15 units/persons, 3 units/machinery, and 1,5 units/machinery. If F (units/year) is a function of value of the farmer (objective functional) that has to be maximized, then it can expressed in the following way:

$F = 2x_3 + (2 - 0,2)x_4 + 4y - 15\rho_m - 3\rho_n - 1,5\rho_t .$ (1.14)

Thus, the formalized mathematical model can be represented in the following way:

$$F = 2x_3 + 1,8x_4 + 4y - 15\rho_m - 3\rho_n - 1,5\rho_t . \Rightarrow \max$$

Considering the constraints:

$x_3 + x_4 + y <= 160$ (constraint on land)

$0,75x_3 - 15p_n <= 0;$

$0,75x_4 + 2,0y - 20p_n <= 0.$ (constraint on harvesters)

$$0{,}5\ x_3 + 0{,}5\ x_4\ - 5\rho_t <= 0$$

$$0{,}3\ x_3 + 0{,}3x_4 + 0{,}5y - 10\rho_t <= 0$$

(constraint on tractors)

$$0{,}75x_3 + 0{,}6y - 15\rho_t <= 0$$

$$0{,}75x_4 + 2{,}0y - 20\rho_t <= 0$$

$$0{,}5x_3 + 0{,}5x_4 - 5\rho_m <= 0$$

$$0{,}3\ x_3 + 0{,}3x_4 + 0{,}5y - 10\rho_m <= 0$$

(constraints on labor resources)

$$2{,}25x_3 + 0{,}6y - 15\rho_m <= 0$$

$$2{,}25x_4 + 4y - 20\rho_m <= 0$$

$$2y <= 160$$

(constraints on crop rotation)

$$3x_3 + 3x_4 <= 320$$

$$x_3,\ x_4,\ y,\ \rho_m,\ \rho_n,\ \rho_t >= 0$$ (condition of nonnegativity)

$\rho_m,\ \rho_n,\ \rho_t$ = integer value (condition on integer values)

This problem can be referred to the class of partial integer problems of linear programming. It has six variables (x_3, x_4, y, ρ_m, ρ_n, ρ_t) and 13 constraints (equations (1.1) - (1.13)). Solving the problem by traditional methods of integer programming (method of Homori and others) provides with the following **optimal solution*:* F = 204, x_3 = 80, x_4 = 0, y = 80, ρ_n = 8, ρ_m = 8, ρ_t = 16.** Further, we shall consider model solution using GAMS.

Model 2.

Now let's consider a special problem of linear programming, the so-called **transportation problem.** General concept of the transportation problem is in defining an optimal solution for delivering some cargo (m) from points of departure *A_1, A_2, ..., A_m,* to points of destination *B_1, B_2, ... , B_n.*

Minimal cost of transportation or maximum delivery time can serve here as a criterion of optimality. Consider the following problem:

Three flower mills A_1, A_2,A_3, produce 110, 190, and 90 tons of flower daily. Four bakeries B1, B2, B3, B4 with daily demand of 80, 60, and 170, and 80 tons of flower consume the flower. Transport tariffs per1 ton of flower from flower mills to bakeries are given in the Table bellow:

Table 1.

Points of Departure	**Points of Destination**				**Stocks**
	B_1	**B_2**	**B_3**	**B_4**	
A_1	8	1	9	7	**110**
A_2	4	6	2	12	**190**
A_3	3	5	8	9	**90**
Demand	**80**	**60**	**170**	**80**	**∑=390**

It is required to develop a plan of flower transportation with minimal transportation costs.

Let us proceed to the **construction of the mathematical model** of the problem, i.e. considering the transportation problem where optimality criterion is associated with minimal costs:

- c_{ij} is a variable for a transport tariffs for a unit of cargo (1 *ton of flower from flower mills to each bakery)* from point of departure i (flower mills) to points of destination j (bakeries);

- a_i is a variable for stocks of cargo at the point of departure *i* (a_1=110, a_2=190 и a_3=90 - production of flower mills);

- b_j is a variable for cargo demand in the point of destination j (b_1=80, b_2=60, b_3=170, and b_4=80 – demand of bakeries);

- x_{ij} - quantity of cargo units to be transported from the point of departure i to point of destination j (total flower transfer in tons from flower mills to bakeries).

Thus, the mathematical problem can be represented in the following way:

$$F(x_{ij}) = \min \left(\sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij}\right) \qquad (2.1)$$

If the following conditions are met:

$$\sum_{i=1}^{m} x_{ij} = b_j \quad (j=1,...,n) \text{ - consumer demands are satisfied;} \qquad (2.2)$$

$$\sum_{j=1}^{n} x_{ij} = a_i \quad (i=1,...,m) \text{ – condition of balance (complete export of cargo is guaranteed)} \qquad (2.3)$$

$$x_{ij} >= 0 \qquad (i=1,...,m; j=1,...,n) \qquad (2.4)$$

Then, formalized mathematical model of the problem looks in the following way:

It is required to minimize:

$$F = 8x_{11}+ x_{12}+ 9x_{13}+ 7x_{14}+ 4x_{21}+ 6x_{22}+ 2x_{23}+ 12x_{23}+ 3x_{31}+ 5x_{32}+ 8x_{33}+ 9x_{34}$$

Considering:

$$x_{11}+ x_{21} + x_{31} = 80$$
$$x_{12}+ x_{22} + x_{32} = 60$$
$$x_{13}+ x_{23} + x_{33} = 170 \quad \text{satisfaction of consumer demands}$$
$$x_{14}+ x_{24} + x_{34} = 80$$

$$x_{11} + x_{12} + x_{13} + x_{14} = 110$$
$$x_{21} + x_{22} + x_{23} + x_{24} = 190 \quad \text{condition of balance}$$
$$x_{31} + x_{32} + x_{33} + x_{34} = 90$$

(complete export of flower from all the flower mills is guaranteed)

$$x_{11}, x_{12},..., x_{34} >=0 \quad \text{(nonnegativity condition).}$$

The problem refers to the class of linear programming problems. It has twelve variables ($x_{11}, x_{12},..., x_{34}$) and 8 constraints (equations (2.2) - (2.4)). Solving the problem by traditional methods of linear programming **(Method of Potentials)** provides with the following **optimal solution: F = 1280 , $x_{11} = 0, x_{12} = 60, x_{13}= 0, x_{14} = 50, x_{21} = 20, x_{22}= 0, x_{23} = 170, x_{24} = 0, x_{31}= 60, x_{32} = 0, x_{33} = 0, x_{34}= 30$.** Furthermore, we shall consider the model solution using GAMS.

Model 3.

Consider the problem associated with agriculture: A producer of the compound feeding stuff must develop a recipe for growing-fattening of pigs. On the one hand, the feeding stuff must have a minimal cost. On the other, its nutrient availability must be corresponding to certain requirements. As a minimum, the feeding stuff must have concentration of: digestible energy (ПЭ) - 13 Mjoul/kg, raw protein (ПСП) - 12%, lysine - 6%, and dietary fiber- not exceeding 5%. In addition, the feeding stuff must contain mineral and vitamin supplements not less than two particles per 100. Necessary ingredients of the feeding stuff (including specified digestive values, content of fiber) and costs are given in the Table below:

Ingredient	Digestible energy MJoul/kg	Raw protein Gram/kg	Lysine Gram/kg	Fiber %	Cost $/ton
Soy flower	15.0	41.0	28.0	5.2	145
Off-corn	11.9	9.9	6.4	7.5	110
Corn flower	14.5	7.3	2.6	2.0	160
Barley flower	12.7	7.7	3.2	4.6	130
Mineral and vitamin supplements	-	-	-	-	400

It is required to define an optimal content of the mixture. To what extent must maize flower be cheaper to be included into the optimal feeding stuff?

Let us proceed to the **construction of the mathematical model** of the problem.

- Assume that 1kg of the feeding stuff contains $x_1$kg of soy flower, $x_2$kg of off-corn, $x_3$kg of maize flower, $x_4$kg of barley, and $x_5$kg of mineral and vitamin supplements.

- Assume F is a price of 1kg of the mixture that has to be minimized:

$$F = 14,5x_1 + 11x_2 + 16x_3 + 13x_4 + 40x_5 \quad (3.1)$$

- Constraint on the aggregate mass:

$$x_1 + x_2 + x_3 + x_4 + x_5 = 1 \quad (3.2)$$

- Energy constraint:

$$15x_1 + 11,9x_2 +14,5x_3 +12,7x_4 >= 13 \quad (3.3)$$

- Protein constraint:

$$41x_1 +9,9x_2 +7,3x_3 +7,7x_4 >= 12 \quad (3.4)$$

- Lysine and fiber constraint:

$$28x_1 + 6,4x_2 + 2,6x_3 + 3,2x_4 >= 6 \quad (3.5)$$

$$5,2x_1 + 7,5x_2 + 2x_3 + 4,6x_4 <= 5 \quad (3.6)$$

- Mineral and vitamin constraint:

$$x_5 >= 0,02 \quad (3.7)$$

- Nonnegativity factor:

$$x_1, x_2, x_3, x_4, x_5 >= 0 \qquad (3.8)$$

Thus, formalized mathematical model looks the following way (including additional non-negative variables):

$$F = 14{,}5x_1 + 11x_2 + 16x_3 + 13x_4 + 40x_5 \Rightarrow \min$$

Considering:

$$x_1 + x_2 + x_3 + x_4 + x_5 = 1 \quad \text{(Constraint on aggregate mass)}$$

$$15x_1 + 11{,}9x_2 + 14{,}5x_3 + 12{,}7x_4 + x_6 = 13 \quad \text{(Energy constraint)}$$

$$41x_1 + 9{,}9x_2 + 7{,}3x_3 + 7{,}7x_4 + x_7 = 12 \quad \text{(Protein constraint)}$$

$$28x_1 + 6{,}4x_2 + 2{,}6x_3 + 3{,}2x_4 + x_8 = 6 \quad \text{(Lysine constraint)}$$

$$5{,}2x_1 + 7{,}5x_2 + 2x_3 + 4{,}6x_4 + x_9 = 5 \quad \text{(Fiber constraint)}$$

$$x_5 + x_{10} = 0{,}02 \quad \text{(Constraint on mineral and vitamin supplements)}$$

$$x_1, x_2, x_3, x_4, x_5, x_6, x_7, x_8, x_9, x_{10} >= 0 \quad \text{(Nonnegativity condition)}$$

This problem is related to the class of problems on linear programming. It has five variables (x_1, x_2, x_3, x_4, x_5) and 7 constraints (equations (3.2) - (3.8)). Solution of the problem by traditional methods of linear programming (Simplex Method, etc.) provides with the following *optimal solution*: **F = 13.7; $x_1 = 0.28$, $x_2 = 0.112$, $x_3 = 0$, $x_4 = 0.589$, $x_5 = 0.020$.** The discounted optimal cost of the non-basis variable x_3 is 0,3664. It means that the price of the maize flower must drop by $367 prior for using it in the optimal mixture. Furthermore, we shall consider the solution of the problem using GAMS.

Model 4.

Consider the following problem on defining a ration for a Friesian cow. The weight of the cow is *600 kg. Beginning from the second week of lactation it gives 25 kg of milk every day. The cow's metabolic energy needs (MЭ) are 185Mjouls/day. Marginal feed consumption equal to 15 kg of dry substance (CB) daily. Available feed is silage (content of MЭ - 9 Mjouls/kg of CB, and compound feeding stuff (content of MЭ - 12,5 Mjouls/kg of CB).*

It is necessary to define a ration with minimum content of concentrates. (It must be kept in mind that consumption of 1 kg of feeding stuff decreases consumption of silage by 0,72 kg).

Let us proceed to **the process of construction a mathematical model** of the problem.

- Let us assume that x_1 and x_2 is a quantity of silage and feeding stuff (kg CB/day) respectively.
- Assume that *F kg* is concentrates to be minimized. Then the functional of the problem takes the following form:

$$F = x_2 \Rightarrow \min \qquad (4.1)$$

Considering the following constraints:

$9x_1 + 12{,}5x_2 >= 185$ (Constraint on МЭ) (4.2)

$x_1 + 0{,}72x_2 <= 15$ (Constraint based on the need of the animal for food) (4.3)

$x_1, x_2 >= 0$ (condition of nonnegativity) (4.4)

This problem is also referred to the class of problems of linear programming with two variables (x_1, x_2) and 3 constraints (equation (4.2) - (4.4)). Solution of the problem through using traditional methods of linear programming (Graphical Method, etc.) provides with the following **optimal solution: F = 8.31; x_1 = 9.02 , x_2 = 8.31.** Furthermore, consider the solution of the model on the basis of GAMS.

Model 5.

Consider the problem of optimal use of areas under crops: *A farmer has 200 ha of available land of high quality, 100 ha of land of low quality, and $US150,000 of capital. There is also 5,000 man/hours of available labor resources (the farmer and his family. Additional labor costs equal to $US 2,5 per hour. Potential crops are wheat, barley, potatoes, sugar beats, and colza. The information on each crop is given in Table below.*

It is required to develop a plan of using lands under crops for maximizing profits of the farmer.

Let us proceed to the **construction of the mathematical model** of the problem.

Crops	Expected yields (ton/ha)		Demand for labor resources (man - hours/ha)	Other costs (seeds, fertilizers, irrigation) $US/ha	Expected prices ($US/ha)
	High quality lands	Low quality lands			
Spring wheat	4,6	3,4	12,4	135	112
Spring barley	4,8	3,5	12,4	117	107,5
Potatoes	40	20	72,5	725	60
Sugar beats	45	28	67,3	365	25
Colza	2,5	1,5	14,0	185	225

- Indices:
  - X_{hw} - area (ha), high quality land under spring wheat;
  - X_{lw} - area (ha), low quality land under wheat;
  - X_{hb} - area (ha), high quality land under barley;
  - X_{lb} - area (ha), low quality land under spring wheat;

X_{hp} - area (ha), high quality land under potatoes;
X_{lp} - area (ha), low quality land under spring potatoes;
X_{hs} - area (ha), high quality land under sugar beats;
X_{ls} - area (ha), low quality land under sugar beats;
X_{ho} - area (ha), high quality land under colza;
X_{lo} - area (ha), low quality land under colza;

- Expected profits from crops: $US/ha = expected price - labor costs – other costs. For example, profits from the spring wheat harvested on the high quality land = 112*4,6 - 12,4*2,5 - 135 = 349.2 dollars/ha. Using the same procedure, we can define profits from other crops.

- Let us assume that F is a profit (dollars) to be maximized. Then, the objective functional of the problem takes the following way:

$$F = 349{,}2\, X_{hw} + 214{,}8X_{lw} + 368X_{hb} + 228.25X_{lb} + 1493.75X_{hp} + 293{,}75X_{lp} + + 591{,}75X_{hs} + 166{,}75X_{ls} + 342{,}5X_{ho} + 117{,}5X_{lo} \quad (5.1)$$

- Considering the following constraints:

$$X_{hw} + X_{lw} + X_{hp} + X_{hs} + X_{ho} <= 200 \text{ (constraint on the high quality land)} \quad (5.2)$$

$$X_{lw} + X_{lb} + X_{lp} + X_{ls} + X_{lo} <= 100 \text{ (constraint on the low quality land)} \quad (5.3)$$

$$135(X_{hw} + X_{lw}) + 117(X_{hb} + X_{lb}) + 725(X_{hp} + X_{lp}) + + 365(X_{hs} + X_{ls}) + 185(X_{ho} + X_{lo}) <= 150\,000 \text{ (constraint on the capital for covering non-labor costs)} \quad (5.4)$$

$$166(X_{hw} + X_{lw}) + 148(X_{hb} + X_{lb}) + 906{,}25(X_{hp} + X_{lp}) + + 533{,}25(X_{hs} + X_{ls}) + 220(X_{ho} + X_{lo}) <= 162\,500 \text{ (constraint on the capital)} \quad (5.5)$$

This problem refers to the type problems of linear programming that has ten controlled variables (X_{hw},..., X_{lo}) and four constraints (equation (5.2) - (5.5)). Solution of the problem by traditional methods of linear programming (Simplex Method and others) provides with the following **optimal solution*: Plan of optimal use of area under crops: F = 271764.36 dollars; X_{hp} = 155.75 , X_{hb} = 44.25, и X_{lb} = 100 .*** Furthermore, we shall consider the solution of the model using GAMS.

Thus, we have considered mathematical formalizations of five models from five various areas. Now, let’s consider the second point.

2. Model Implementation

Despite the chosen type of models, it is also necessary to choose an implementation form, as well as means of optimization and strategy for computation of solutions.

The optimization model can be written explicitly and then programmed in accordance with the chosen algorithm for the solution of the problem.

GAMS allows easily solve the shown above optimization problems. Consider the use of the GAMS language for solution of optimization models (see Model 1. – Model 5). Implementation of models using GAMS are provided below:

***** GAMS file for Model № 1**
***** Mixed Integer Linear Program Version**
***** Sobir.T. Navruzov**

Sets
i type of variable / x3,x4,y,pm,pn,pt /
j type of constraint equations / equ1*equ13 / ;

Parameters
c coefficients in objective function
/ x3 2.0
x4 1.8
y 4.0
pm -15.0
pn -3.0
pt -1.5 /

b right hand sides of constraint equations
/equ1 160.0
equ2*equ11 0.0
equ12 160
equ13 320 / ;

Table a(i, j) coefficients in constraint equations

	equ1	***equ2***	***equ3***	***equ4***	***equ5***	***equ6***	***equ7***	***equ8***	***equ9***	***equ10***	***equ11***	***equ12***	***equ13***
x3	**1**	**0.75**	**0**	**0.5**	**0.3**	**0.75**	**0**	**0.5**	**0.3**	**2.25**	**0**	**0**	**3**
x4	**1**	**0**	**0.75**	**0.5**	**0.3**	**0**	**0.75**	**0.5**	**0.3**	**0**	**2.25**	**0**	**3**
y	**1**	**0**	**2**	**0**	**0.5**	**0.6**	**2**	**0**	**0.5**	**0.6**	**4**	**2**	**0**

```
   pm    0     0     0     0     0     0     0    -5    -10    -15    -20    0
0
   pn    0   -15   -20     0     0     0     0     0      0      0      0    0
0
   pt    0     0     0    -5   -10   -15   -20     0      0      0      0    0
0  ;

        Variables
              fun;

        INTEGER variables

                x(i);

        Equations
                obj        objective function
                const(j)     constraint equations ;

        obj  ..   fun  =e=  sum ( i, c(i)*x(i) )  ;

        const(j)  ..   sum(i, a(i,j)*x(i)) =l= b(j) ;

        model  exam1MIP / all/ ;

        option reslim = 17000000

        option iterlim = 17000000

        solve  exam1MIP using MIP maximizing fun;

        display x.l ;

        file res / agro_MIP.txt/;
        put res;
        put "    Finding optimal solution  "
        put "x3=", put x.l('x3'):6:2 , put /
        put "x4=", put x.l ('x4'):6:2 , put /
        put "y =", put x.l('y '):6:2 , put /
        put "pm=", put x.l('pm'):6:2 , put /
        put "pn=", put x.l('pn'):6:2 , put /
        put "pt=", put x.l('pt'):6:2 , put /
        put "objective value I = ", put fun.l:6:2;
```

Model running provides with the following results:

Finding optimal solution

x3 = 80.00
x4 = 0.00
y = 80.00
pm = 16.00
pn = 8.00
pt = 8.00

objective value I = 204.00

As one can see, optimal solutions for **Model 1** using GAMS and traditional methods of integer programming (Method of Homori) coincide.

Consider the implementation of **Model 2** on the basis of GAMS:

```
*** GAMS file for Model №2
*** Linear Program Version
*** Sobir.T. Navruzov

Sets
        i  flower mill / a1,a2,a3 /
        j bakery / b1, b2,b3,b4 / ;

Parameters
           a(i)  daily production of the flower mill
              / a1     110
                a2     190
                a3     90 /


           b(j)  demand of bakeries
              /b1     80
               b2     60
               b3     170
               b4     80 /  ;

Table c(i, j) tariff for delivering 1 ton of flower from a flower mill to a bakery

          b1    b2    b3    b4
    a1     8     1     9     7
    a2     4     6     2    12
    a3     3     5     8     9 ;

Variables
        fun   total cost of transportation
      x(i,j)    quantity of flower delivered from point A to point B
```

```
Positive variables

        x;

Equations
        obj          objective function
        sypply(i)    law of conservation
        demand(j)    demand of consumers

obj ..   fun =e= sum ((i,j), c(i,j)*x(i,j) ) ;

supply(i)    ..   sum(j, x(i,j)) =e= a(i) ;
demand(j)  ..   sum(i, x(i,j)) =e= b(j) ;

model transLP / all/ ;

option reslim = 17000000

option iterlim = 17000000

solve transLP using LP minimizing fun;

display x.l,x.m ;

file res / tras_res.txt/;
put res;
put"        Finding optimal solution" put //
put"  x(i,1)=",put loop(i,put x.l(i,'b1'):12:3;) put /
put"  x(i,2)=",put loop(i,put x.l(i,'b2'):12:3;) put /
put"  x(i,3)=",put loop(i,put x.l(i,'b3'):12:3;) put /
put"  x(i,4)=",put loop(i,put x.l(i,'b4'):12:3;) put //
put "       Objective value F=",put fun.l:9:3;
```

Model running provides with the following result:

Finding optimal solution

x(i,1) =	**0.000**	**20.000**	**60.000**
x(i,2) =	**60.000**	**0.000**	**0.000**
x(i,3) =	**0.000**	**170.000**	**0.000**
x(i,4) =	**50.000**	**0.000**	**30.000**

Objective value F =1280.00

As one can see, optimal solutions for **Model 2** found by GAMS and traditional methods of integer programming (Method of Potentials) coincide.

Consider implementation of **Model 3** on the basis of GAMS.

```
*** GAMS file for Model №3
*** Linear Program Version
*** Sosir T. Navruzov

Sets
        i  type of variable            / x1,x2,x3,x4,x5,x6,x7,x8,x9,x10 /
        j  type of constraint equations / equ1,equ2,equ3,equ4,equ5,equ6 / ;

Parameters
          c    coefficients in objective function
            / x1      14.5
              x2      11.0
              x3      16.0
              x4      13.0
              x5      40.0
              x6      0.0
              x7      0.0
              x8      0.0
              x9      0.0
              x10     0.0 /

          b  right hand sides of constraint equations
            /equ1     1.0
             equ2     13.0
             equ3     12.0
             equ4     6.0
             equ5     5.0
             equ6     0.02 /  ;

Table a(i, j) coefficients in constraint equations

          equ1   equ2   equ3   equ4   equ5   equ6
    x1     1.0   15.0   41.0   28.0    5.2    0.0
    x2     1.0   11.9    9.9    6.4    7.5    0.0
    x3     1.0   14.5    7.3    2.6    2.0    0.0
    x4     1.0   12.7    7.7    3.2    4.6    0.0
    x5     1.0   0.0     0.0    0.0    0.0    1.0
    x6     0.0   -1.0   0.0    0.0    0.0    0.0
    x7     0.0    0.0  -1.0    0.0    0.0    0.0
    x8     0.0    0.0   0.0   -1.0    0.0    0.0
    x9     0.0    0.0   0.0    0.0    1.0    0.0
```

```
    x10       0.0     0.0     0.0     0.0      0.0    1.0 ;

Variables
      fun;
Positive variables
                        x(i);
Equations
        obj         objective function
        const(j)    constraint equations ;

obj         ..    fun  =e=  sum ( i, c(i)*x(i) )  ;
const(j)  ..    sum(i, a(i,j)*x(i)) =e= b(j) ;

model  model_33LP / all/ ;

solve  model_33LP using LP minimizing fun;

display x.l ;
file res / model_33.txt/;
put res;
put"          Finding optimal solution" put //
put "x1=", put   x.l('x1'):6:3 , put /
put "x2=", put   x.l('x2'):6:3 , put /
put "x3=", put   x.l('x3'):6:3 , put /
put "x4=", put   x.l('x4'):6:3 , put /
put "x5=", put   x.l('x5'):6:3 , put /
put "x6=", put   x.l('x6'):6:3 , put /
put "x7=", put   x.l('x7'):6:3 , put /
put "x8=", put   x.l('x8'):6:3 , put /
put "x9=", put   x.l('x9'):6:3 , put /
put "x10=", put   x.l('x10'):6:3 , put /

put "Objective value",    put   fun.l:6:3  ;
```

Model running provides with the following result:

Finding optimal solution

x1	**=**	**0.280**	**x6**	**=**	**0.000**
x2	**=**	**0.112**	**x7**	**=**	**5.108**
x3	**=**	**0.000**	**x8**	**=**	**4.491**
x4	**=**	**0.588**	**x9**	**=**	**0.000**
x5	**=**	**0.020**	**x10**	**=**	**0.000**

Objective value F =13.736

It is obvious that the optimal solution for **Model 3** provided by GAMS and traditional methods of linear programming (Simplex Method) coincide. It must be noted that marginal values for a non-basis variable x_3 are equal to 3.36. This value coincides with the value found manually using Simplex Method. This fact once again shows the reliability of GAMS for solving optimization problems.

Consider implementation of **Model 4** on the basis of GAMS.

```
*** GAMS file for Model № 4
*** Linear Program Version
*** Sosir T. Navruzov
Sets
         i  type of variable            / x1,x2 /
         j  type of constraint equations / equ1, equ2 / ;
Parameters
             c    coefficients in objective function
                / x1      0.0
                  x2      1.0 /
            b  right hand sides of constraint equations
                /equ1     185.0
                 equ2     15.0 /  ;

Table a(i, j) coefficients in constraint equations
                  equ1    equ2
   x1               9.0     1.0
   x2              12.5     0.72  ;
Variables
       fun;
Positive variables
                       x(i);
Equations
         obj         objective function
         equ1        fist equation
         equ2        second equation;

obj  ..    fun  =e=  sum ( i, c(i)*x(i) )  ;
equ1 ..    a('x1','equ1')*x('x1')+a('x2','equ1')*x('x2') =g= b('equ1');
equ2 ..    a('x1','equ2')*x('x1')+a('x2','equ2')*x('x2') =l= b('equ2');

model  ml_134LP / all/ ;
solve  ml_134LP using LP minimizing fun;
display x.l ;
file res / model134.txt/;
put res;
put "            Finding solution        "
put "x1=", put   x.l('x1'):6:3 , put /
```

```
put "x2=", put   x.l('x2'):6:3 , put /
put "Objective value",    put   fun.l:6:3  ;
```

running of the model provides with the following result:

Finding optimal solution

x1 =   9.020
x2 =   8.306

Objective value F =8.306

As one can see, optimal solutions for **Model 4** found using GAMS and traditional methods of linear programming (Graphical Method) coincide.

Consider implementation of Model 5 with GAMS.

```
*** GAMS file for Model №5
*** Linear Program Version
*** Sosir T. Navruzov

Sets
     i  type of variable           / xhw,xlw,xhb,xlb,xhp,xlp,xhs,xls,xho,xlo /
     j  type of constraint equations / equ1,equ2,equ3,equ4 / ;

Parameters
        c    coefficients in objective function
           / xhw      349.2
             xlw      214.8
             xhb      368.0
             xlb      228.25
             xhp      1493.75
             xlp      293.75
             xhs      591.75
             xls      166.75
             xho      342.5
             xlo      117.5 /

        b  right hand sides of constraint equations
           /equ1     200.0
            equ2     100.0
            equ3     150000.0
            equ4     162500.0  /  ;

Table a(i, j) coefficients in constraint equations
        equ1    equ2   equ3     equ4
```

```
   xhw      1.0     0.0     135.0     166.0
   xlw      0.0     1.0     135.0     166.0
   xhb      1.0     0.0     117.0     148.0
   xlb      0.0     1.0     117.0     148.0
   xhp      1.0     0.0     725.0     906.25
   xlp      0.0     1.0     725.0     906.25
   xhs      1.0     0.0     365.0     533.25
   xls      0.0     1.0     365.0     533.25
   xho      1.0     0.0     185.0     220.0
   xlo      0.0     1.0     185.0     220.0   ;

Variables
                 fun;
Positive variables
                 x(i);
Equations
        obj        objective function
        const(j)     constraint equations ;

obj       ..   fun  =e=  sum ( i, c(i)*x(i) )  ;

const(j)  ..   sum(i, a(i,j)*x(i)) =l= b(j) ;

model  model122LP / all/ ;
solve  model122LP using LP maximizing fun;
display x.l ;
file res / model122.txt/;
put res;
put "         Finding optimal solution  "//
put "xhw=", put   x.l('xhw'):12:3 , put /
put "xlw =", put   x.l('xlw'):12:3 , put /
put "xhb=", put   x.l('xhb'):12:3 , put /
put "xlb =", put   x.l('xlb'):12:3 , put /
put "xhp=", put   x.l('xhp'):12:3 , put /
put "xlp =", put   x.l('xlp'):12:3 , put /
put "xhs=", put   x.l('xhs'):12:3 , put /
put "xls =", put   x.l('xls'):12:3 , put /
put "xho=", put   x.l('xho'):12:3 , put /
put "xlo=", put   x.l('xlo'):12:3 , put /

put "objective value",    put   fun.l:12:3  ;
```

The model running provides with the following result:

Finding optimal solution

xhw= 0.000
xlw= 0.000
xhb= 44.247
xlb= 100.000
xhp= 155.753
xlp= 0.000
xhs= 0.000
xls= 0.000
xho= 0.000
xlo= 0.000

Objective value 271764.367

It is obvious that an optimal solution of **Model 5** found using GAMS and traditional methods of linear programming (Simplex Method) coincide.

Thus, we used GAMS for solving optimization problems (see Models 1-5). Let us proceed now to assessing solutions and considering some specifics of the sensitivity analysis in linear programming.

3. Solution Assessment

Optimization studies are not finalized on the stage of finding optimal solutions. The most important part of the study is associated with verification of the correctness of solutions and sensitivity analysis. The most important part is not only to find a solution, but the information associated with it, which allows to understand its main properties. Main results of the study are connected with answers to questions like: What constraints are active for the solution? What is associated with the main part of the cost? What is the sensitivity of the solution to variations of parameters?

Active constraints indicate to the restricted nature of possibilities of the system, or that the design of the system can not be improved. The cost value is indicative of the block of the system parameters to be improved. Sensitivity of solutions to changes of parameters indicates the parameters to be improved for finding an optimal solution. Let us briefly consider methods of justification of solutions and conducting sensitivity analysis.

3.1. Justification of Correctness of Solutions

First and foremost, when studying optimization results it is necessary **to define if solutions are justified.** It is generally assumed that a solution is justified if it has some appropriate feasible optimal condition. Feasible condition is only one of the possible conditions of the system. As a rule, if a model properly reflects the behavior of the system it has constraints and boundaries. This allows to find a mathematical solution, which reflects a feasible physical condition of the system. However, all the models are correct only to some extent, as well as all the relationships are true within some boundaries, and any information is relatively accurate.

If it is proved that the solution is feasible, it is necessary to define whether it is optimal or not. We are not speaking about the mathematical proof of fulfilling necessary conditions of the optimal criterion, but interpretation of results and understanding whether the solution is optimal. For trusting the solution, it is necessary to understand the reasons why the variables of the solution acquire these values. Otherwise, the optimality of the solution must be taken as a result of application of mathematics and a computer.

Thus, the recommended general methodology is as follows:

- simplify a model for using simple algebraic methods;
- get optimal solution from auxiliary models as a function of main variables of models;
- by means of auxiliary models make a number of forecasts and check them on general models;
- if optimization calculations confirm trends developed by auxiliary models, the success in explaining model characteristics is achieved.

In general, thereby several auxiliary models can be explored, each reflecting some main factors or characteristics of the general model or system.

The considered above models (Models 1-5) are refereed to the first point with simple algebraic methods used for their solution.

3.2. Analysis of Sensitivity

The following stage of evaluation of the solution implies defining its sensitivity to changing the model parameters or source data. Such studies are known as *analyses of sensitivity*. The purposes of detailed analysis of sensitivity are as follows:

- Finding the parameters rendering most influence upon the optimum solution. If such parameters exist, then it might be advisable to consider an issue of adjusting the corresponding system characteristics.
- Clarification of data on additions or system modifications for improving its performance characteristics.
- Determination of impact on the system caused by inadequate parameters. Some of the values of model parameters might be known with big inaccuracy. Analysis of sensitivity shows whether it is worth to define the values of these parameters more accurately.
- Defining the possible system reactions to uncontrolled outside impacts.

Notice that in many events detailed analysis of sensitivity turns out to be more useful, than optimum solution.

The illustration of practical application of the sensitivity analysis is given below.

Model 1 (Example)

We have found the following optimum result for **Model 1**: Crop X must be harvested within period 3 (**otherwise farmer incurs a loss in the size of 0.2 units/units of area**) on the land with the area of 80 units. Crop Y is also planted on the area of 80 units (**only 160 units of land are available**).

In addition, demand for combines and tractors (for harvesting, plowing and sowing) are 8 units, and labor force – 16 people. Now let us experiment with the input data of the model:

- First, let us change the value of the available area;
- Then, the value of expenses if and when harvesting is done in period 4.

I). If 160 ⇒ 180, then optimal solution is:

Finding optimal solution
x3 = 92.00 – area under crop X in period 3;
x4 = 8.00 – area under crop X in period 4;
y = 80.00 – area under crop Y;
pm = 17.00 – demand for labor resources;
pn = 10.00 – demand for combines;
pt = 10.00 – demand for tractors;
objective value I = 218.40

II). If 160 ⇒ 180 and costs in the amount of 0.2 ⇒ 1.0, then optimal solution is the following:

Finding optimal solution
x3 = 85.00
x4 = 0.00
y = 80.00
pm = 16.00
pn = 8.00
pt = 10.00
objective value I = 211.40

III). If the costs in the amount of 0.2 ⇒ 1.0, then the optimal solution does not change:

Finding optimal solution
x3 = 80.00
x4 = 0.00
y = 80.00
pm = 16.00
pn = 8.00
pt = 8.00

objective value I = 204.00

The testing results of the sensitivity analysis demonstrate that the found solution is optimal.

Model 6 (Example)

An enterprise produces three types of products. Production requires physical labor, raw materials, and management. Profit to the unit of each type of product is \$10, \$6 and \$4 accordingly. During working days it is possible to use 100 hours of physical labor, 600 tons of raw materials, and 300 hours of management labor. In the table presented below, units of production for three types of products are given. The objective is to maximize profits associated with the production of these three types of products.

Type of product	***Units of production***		
	Physical labor (hours)	Raw materials (tons)	Management labor (hours)
1	1	10	2
2	1	4	2
3	1	5	6

Then, the mathematical model takes the following form:

Maximize:

$$F = 10x_1 + 6x_2 + 4x_3$$

Under the constraints:

$x_1 + x_2 + x_3 <= 100$ (constraints on physical labor)

$10x_1 + 4x_2 + 5x_3 <= 600$ (constraints on raw materials)

$2x_1 + 2x_2 + 6x_3 <= 300$ (constraints on management labor)

$x_1, \quad x_2, \quad x_3 >= 0,$ (condition of nonnegativity)

where x_1, x_2, x_3 denote daily production of products type 1, 2 and 3 accordingly.

Implementation of <u>Model 6</u> using GAMS:

```
*** GAMS file for Model №49
*** Linear Program Version
*** Sosir T. Navruzov

Sets
     i  type of variable           / x1,x2,x3 /
     j  type of constraint equations / equ1,equ2,equ3 / ;
```

```
Parameters
            c    coefficients in objective function
               / x1      10.0
                 x2      6.0
                 x3      4.00 /
             b  right hand sides of constraint equations
               /equ1     100.0
                equ2     600.0
                equ3     300.0 /  ;

Table a(i, j) coefficients in constraint equations
          equ1    equ2   equ3
   x1      1.0     10.0    2.0
   x2      1.0     4.0     2.0
   x3      1.0     5.0     6.0  ;

Variables
                fun;

Positive variables
                      x(i);
*          x.lo('x1')=6.0;
*          x.up('x1')=12.0;
*          x.lo('x2')=4.0;
*         x.up('x2')=10.0;
*          x.up('x3')=6.67;
Equations
          obj         objective function
          const(j)     constraint equations ;

    obj    ..    fun  =e=  sum ( i, c(i)*x(i) )  ;

const(j)  ..    sum(i, a(i,j)*x(i)) =l= b(j) ;

model  model_49LP / all/ ;

solve  model_49LP using LP maximizing fun;

display x.l ;
file res / model_49.txt/;
put res;
put "x1=", put   x.l('x1'):12:3 , put /
put "x2=", put   x.l('x2'):12:3 , put /
put "x3=", put   x.l('x3'):12:3 , put /

put "objective value",    put   fun.l:12:5  ;
```

Table 1 provides with the solution of **Model 6** found by GAMS. Notice that optimal solution is associated with the production of type 1 product (33.33 units per day) and type 2 (66.67 units per day).

Hidden prices define increase of maximum profit if an additional unit of some resource is used.

Table 1

Optimal solution: $x_1 = 33.33$, $x2 = 66.67$, $x_3 = 0$
Optimal value of the objective function: maximum profit: F = 733.33 dollars

Hidden prices: for equ1 = 3.33 dollars,
for equ 2 = 0.67,
for equ 3 = 0
Marginal values: for $x_1 = 0$, for $x_2 = 0$, for $x_3 =$ 2,67

Range of fluctuation of the objective function:

Variable	Lower boundary	Current value	Upper boundary
x_1	6	10	15
x_2	4	6	10
x_3	- ∞	4	6,67

Range of changing of right hand parts

equ	Lower boundary	Current value	Upper boundary
1	60	100	150
2	400	600	1000
3	200	300	∞

Use of physical labor is associated with maximum profit, since it provides with additional profit of 3 dollars 33 cents for each additional working hour. Hidden prices of resources are applicable only under the condition that changes of quantity do not exceed the boundaries of right hand part of the table. In other words, the profit rise of 3.33 dollars for each additional hour of physical labor is true until the total labor cost does not exceed 150 hours.

It is worth noting that changes of any part of the right hand column affect optimal solutions. *Thus, under these conditions only type 1 and 2 products will be profitable for production. However, the number of relationships can vary.*

The analysis shows that the optimal solutions will not change until the profit associated with type 1 is within 6 - 15 dollars. Obviously, the maximum profit will be changing. For example, if profit per unit of production rises from \$10 to 12, then the optimal solution does not change and maximum profit increases up to 733.33 + (12-10)*(33,33) = \$799.99 (approximately = \$800).

Notice that production of type 3 is not profitable. Its marginal value indicates how much the maximum profit decreases when this type of product is produced. Therefore, further inputs into production of type 3 do not affect optimal solution and the value of maximum profit. For the production of this type to become profitable, it is necessary to have a profit per unit equaling to \$6.67 (discounted cost + marginal value).

Thus, intervals of coefficients of the objective function given in Table 1 define the sensitivity of the optimal solution associated with changes of profit from three types of products.

In conclusion it must be noted that **GAMS is a powerful and reliable tool for solving optimization problems**. It is a universal modeling instrument allowing specialists to conduct experimental work without taking much trouble about methods of optimization.

3.4. Major Provisions and Principles for Optimizing the Use of Water and Energy Resources of the Syr Darya Basin

This section is the most important and intricate in the whole work. The existence of several individual blocks, BVO model, planning zone model, UDC model, shows that. Unfortunately, all these models operate only the modes already established. Optimization of the latter is available only within a single model coordinating national interests of individual republics for the whole region. This coordination under market conditions is possible only at the expense of corresponding compensations. Naturally, to approve such a model and assess the incidence of individual factors you need time and practice. Therefore, below we considered different options of such a general model.

1. Mathematical Model of Kairakkum Reservoir Operation

At the first stage, we solve problems of seasonal flow regulation. Major blocks here are national optimization models created individually for each republic. The criterion of all these models is maximized benefits for each national state. The final result will be an operation mode of national reservoirs and a flow mode on boundaries with other republics.

We intend to coordinate national models in the future by market methods and special bilateral and multilateral agreements between republics.

According to this, we can conditionally divide the entire analyzed area of the Syr Darya Basin into two zones: *the water demand formation zone* and *the water supply formation zone.* The first zone includes Kazakhstan and Uzbekistan; the second zone includes Kyrgyzstan and Tajikistan.

For republics of different zones, both model-building schemes and their interrelations differ considerably.

It seems that the optimization model for Kazakhstan and Uzbekistan will be developed based on the criterion of maximized agricultural productivity in terms of money or quantity. Planning zones existing in a republic will be the basis for the optimization model, and accordingly this model will incorporate several submodels.

The result of calculations on these models will be defined water demand of a republic. This water demand will be expressed in the form of a chart mainly for the growing season for the Syr Darya River section, which indicates the border between the two zones specified above. Since water demands of Kazakhstan and Uzbekistan do not depend on each other, we determine their total amount for the whole demand area by simple summing.

For Kyrgyzstan and Tajikistan optimization models will be developed based on maximized electric power generation in winter, the period of the shortest supply[5].

For Kazakhstan and Uzbekistan included in the demand area, we can determine demands in pure form if we can say so. Unlike these republics, for the republics of the supply area the hydrological forecast is the required basis of all calculations. The final result here is an operation mode of reservoirs and water consumptions in specific river sections. However, models of the two countries included in the supply area considerably depend on each other. We may say that they are connected in series. Output data of the Kyrgyzstan model are input data for the Tajikistan model. Eventually, for the most part the releases from Kairakkum Reservoir determine a resulting mode for the entire supply area. We may adopt Kairakkum Reservoir as a conditional boundary between *the water supply area and the water demand area.*

The second stage of attaining the primary objective, i.e. to optimize water and energy use at the regional level, is coordinated national interests of individual republics. The best mechanism for that, as the entire world practice shows, is the market.

The peculiarity of our situation is that on the one hand our situation has pure market features. Kazakhstan and Uzbekistan included in the demand area have higher water demands during the growing season than the republics of the supply area, Kyrgyzstan and Tajikistan, can satisfy. Kazakhstan and Uzbekistan can pay for additional water at the expense of the additional income resulted from the use of this water. In their turn, Kyrgyzstan and Tajikistan has principal feasibility to allocate additional water through changing the mode, but in so doing they suffer losses that should be paid. However, on the other hand losses of Kyrgyzstan and Tajikistan are not absolute. Supplying additional water during the growing season, their hydroelectric power stations generate electricity though needless for these countries in this period.

According to this, in the case under consideration we propose as interrelations between the supply area countries and the demand area countries not a pure market scheme of water purchase and sale, but a compensation scheme. Kazakhstan and Uzbekistan, being supplied with

---

[5] It seems that for Kyrgyzstan the optimization model will be developed with regard to simultaneous satisfying electric power demand in other periods of the year.

additional water they need during the growing season, at the same time take the electric power that Kyrgyzstan and Tajikistan generate using this water. In winter, the period of short supply, Kazakhstan and Uzbekistan return the taken electric power or other energy carriers equivalent to this electric power. Of course, monetary settlements are also possible.

The allocation of additional water received from the supply area is proportional to the share participation in compensatory electric power supplies. In the supply area itself, we propose the following scheme. Seasonal flow regulation to render services to Kazakhstan and Uzbekistan on the cascade that includes Toktogul Reservoir and Kairakkum Reservoir follows a compensation scheme beginning from lower Kairakkum Reservoir. Toktogul Reservoir operates mainly under the energy mode serving national interests. This reservoir takes part in seasonal regulation only in case of emergency. This will make possible to increase winter electric power generation by the Toktogul hydroelectric power station without increasing annual reservoir drawdown and saving it for over-year regulation.

This is the end of the first stage. At the second stage, we solve problems of over-year flow regulation. Only Toktogul Reservoir carries out this regulation. Major consumers of this service are Kazakhstan and Uzbekistan. The scheme of mutual settlements does not principally differ from the specified above. We should note that Kazakhstan and Uzbekistan will not incur additional costs, because the cost of seasonal flow regulation by Kairakkum Reservoir is by an order smaller than the cost of flow regulation by Toktogul Reservoir used for these purposes now.

All interrelations between republics concerning the joint water and energy use under the proposed scheme are formalized through corresponding agreements, bilateral and multilateral, annual and long-term.

The proposed scheme does not principally differ from the scheme that Kyrgyzstan, Kazakhstan, and Uzbekistan apply now. The proposed scheme simply provides equal participation of all countries of Central Asia, including Tajikistan, and extends its incidence to over-year flow regulation.

It is important to note that the model proposed is quite practicable. It operates only physical and volumetric parameters and enables you to avoid practically insoluble contradictions in a single regional complex model, which requires interstate coordination of exchange rates, prices, tariffs, standards, etc.

1.1 Problem Statement and General Requirements to the Model

Consider a simple model of a river basin based on characteristics of the Naryn – Syr Darya Basin. In the mathematical model we consider the following elements: three conventional river reaches in the form of river nodes (upstream to Kairakkum Reservoir, river course downstream from Kairakkum Reservoir, and the downstream), one major tributary, one reservoir (Kairakkum) and one user (a reach owned by Tajikistan in the Syr Darya Basin). The design operation scheme of Kairakkum Reservoir (National Model of Tajikistan) is shown on Figure 1.

The major tributary's flow includes the reach from Toktogul Reservoir to Kairakkum Reservoir, i.e. this is the flow of the Syr Darya River below the Akjar measurement station.

Developing an optimization model for the Syr Darya Basin we adhere to the principle **"from simple to complex"**, i.e. at the initial stage we envisage development of individual national models and further the joining of these models within a general basin model.

For Tajikistan, this national model will be the optimization model controlling the operation mode of Kairakkum Reservoir.
Let us briefly formulate major provisions of this model:

- Primary objective – maximized electric power generation during the ungrowing season;
- Reservoir operation mode – independent regulation;
- Consideration of irrigation interests – in the form of aggregated inflow and constraints imposed by operation modes of pump stations;
- Initial conditions – maximum level by the beginning of the ungrowing season;
- Reference data (**see** Major Parameters and Input Data)

1.2 Reference Data

For this simple model, we gathered needed information about operation modes of Kairakkum Reservoir and water and energy characteristics of the model.

1. In Table 1.1 we presented main parameters of Kairakkum Reservoir

Table 1.1

Total Volume, cu km	Effective Storage, cu km	Dead Storage, cu km	Capacity of HPS, MW	Efficiency of HPS, %	Normal Water Level, m	$Q^{max}_{turbines}$ cu m/s
3.5605	2.6895	0.871	126	0.86	347.8	960

In Table 1.2, we showed evaporation (calculated through a nonlinear function approximated in advance) from the Kairakkum Reservoir basin (cu km).

Table 1.2

1	2	3	4	5	6	7	8	9	10	11	12
0.0078	0.0046	0.0109	0.0365	0.0519	0.0691	0.0705	0.0605	0.0489	0.0307	0.0194	0.0081

In Table 1.3, we showed (a variant of) inflow to Kairakkum Reservoir. This option supposes that Toktogul Reservoir is assigned a constant release, which, in its turn, is considered as inflow to Kairakkum Reservoir (in cu km).

Table 1.3

1	2	3	4	5	6	7	8	9	10	11	12
0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958	0.958

Let us give nonlinear approximation of the main dependences used in the mathematical operation model of Kairakkum Reservoir, namely:

- $V = f(H_{в.б})$ = reservoir storage is a function of the upstream level (see Annex 1);
- $H_{в.б} = f(V)$ = the upstream level is a function of reservoir storage (see Annex 2);
- $S = f(V)$ = reservoir water table is a function of reservoir storage (see Annex 3);
- $H_{н.б.} = f(Q)$ = the downstream level is a function of consumption (see Annex 4);
- $q = f(H_{нетто})$ = specific consumption is a function of head (net) (see Annex 5).

1.3 Optimization Criteria

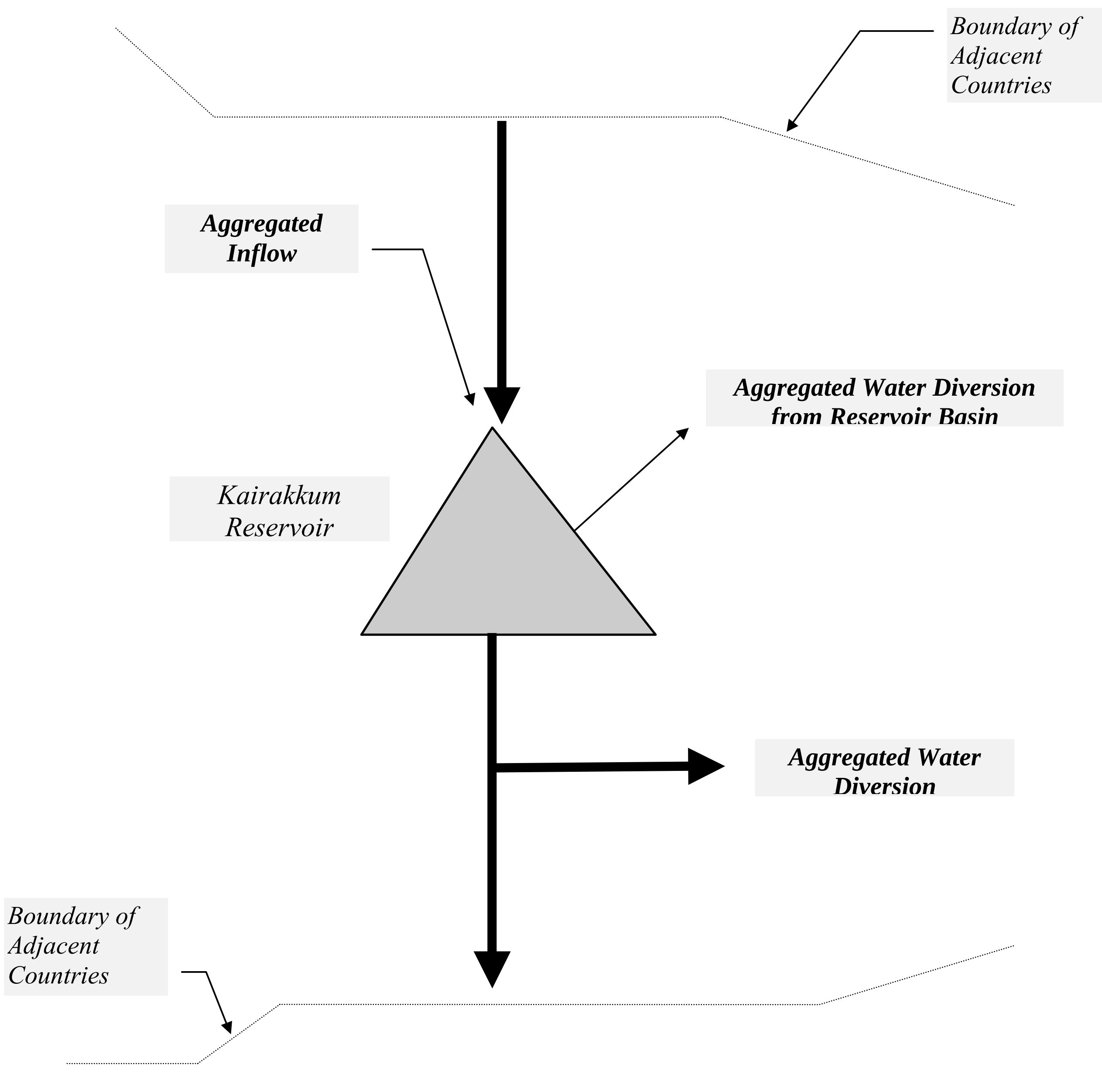
Let us note that modes of water and energy use, which were traditionally established proceeding from interests of Kazakhstan and Uzbekistan more advanced in terms of agriculture, became out of Tajikistan's line. It relates only to the electric power industry. Regarding water management, no problem still arises.

As for energy interests of Tajikistan, the situation is as follows. After the partition of the USSR into republics, the previous scheme of electric power exchange ceased to function. Under that scheme, the electric power generated by the Nurek HPS, but needless for Tajikistan was supplied to Kazakhstan and Uzbekistan. These republics returned this electric power in winter, the period of short supply for Tajikistan. The scheme required from Uzbekistan and Kazakhstan, where thermoelectric power stations were the basis of the energy industry, only to establish appropriate repair schedules. Now this scheme is broken. Consequently, excessive electric power of the Nurek HPS finds no market and the reservoir makes waste releases of water. At the same time, the Kairakkum HPS operating at maximum capacity during this period of the year generates the greatest amount of electric power. In winter, the period of the shortest supply for Tajikistan, the Kairakkum HPS operates at minimum capacity. Hence, in winter Tajikistan has to purchase 300 kWh of electric power in other republics, Turkmenistan and Uzbekistan, on inadvantageous terms.

With regard to the fact that the "North" of Tajikistan is inseparably connected with the "South" and that the "South" supplies 85 % of the "North's" electric power, now the operation of the Kairakkum HPS is just wasteful.

Therefore, we consider maximized electric power generation during the ungrowing season as the optimization criterion in the model of Kairakkum Reservoir operation.

Figure 1. ***Design Operation Diagram of Kairakkum Reservoir (National Model of Tajikistan)***



1.4 Formulation of the Mathematical Model

Consider the problem of maximized one-criterion optimization, where we consider maximized electric power generation during the ungrowing season as the objective function:

It is required to maximize the functional

(1) $$I = \int_{t^*}^{t^{**}} \{W_r(t) * U_{rk}(t)\} dt \Rightarrow \max$$

$t^* < t^{**}$, $[t^*, t^{**}] \in [1,T]$, t^*, t^{**} = periods encompassing the ungrowing season. We consider one year divided into T intervals with the current indexes t, $t \in [1,T]$.

Provided that the following constraints hold:

- **Water Balance in the Reservoir:**

(2) $$\frac{dW_r(t)}{dt} = Q_{vr}(t) + Q_k(t) - U_{rp}(t) - U_{rk}(t) - I_r(t) ,$$

Where:
$W_r(t)$ = storage of the reservoir r during the period t;
$Q_{vr}(t)$ = flow from the tributary node v to the reservoir r during the period t (tributary inflow);
$Q_k(t)$ = flow at the river node k during the period t (main inflow);
$U_{rp}(t)$ = flow from the reservoir r to the user p during the period t;
$U_{rk}(t)$ = flow from the reservoir r to the river node k during the period t;
$I_r(t)$ = evaporation from the reservoir r during the period t;

- $W_r(t)$ should **satisfy the constraint** (physical constraint):

(3) $$W_r^- \leq W_r(t) \leq W_r^+$$

Where:
W_r^- = dead storage level; W_r^+ = normal water level;

- **Initial Conditions:**

(4) $$W_r(1) = W_r^- \text{ (or } W_r^+ \text{)}$$

- **Water Balance in the Area of a Water Entity:**

(5) $$\sum_v Q_{vp}(t) + \sum_k Q_{kp}(t) + \sum_r U_{rp}(t) = \beta_p(t) * P(t) ,$$

Where:
Q_{vp} = flow from the tributary inflow v to the user p during the period t;
Q_{kp} = flow from the river node k to the user p during the period t;
$\beta_p(t)$ = coefficient defining the water consumption share of the user p during the period t;

P(t) = monthly water consumption for irrigation and non-irrigation purposes (aggregated water diversion).

- **Water Constraint:**

(6) $$\sum_{v} Q_{vp}(t) + \sum_{v} Q_{vk}(t) + \sum_{v} Q_{vr}(t) \leq V(t)\ ,$$

Where:
Q_{vk} = flow from the tributary node v to the river node k during the period t;
Q_{vp} and Q_{vr} we described above (see (2) and (5)).
V(t) = monthly inflow from surface sources.

- **Water Balance at Major River Nodes:**

(7) $$Q_k(t) = V_0(t) + \sum_{r} U_{rk}(t) + \sum_{v} Q_{vk}(t) + \sum_{k} Q_{kp}(t) - \sum_{k} \alpha * Q_{kp}\ (t=t^{*}; t=t^{**}),$$

Where:
$V_0(t)$ = river node equal to the main channel, main inflow to the reservoir;
α = coefficient defining the water consumption share of the user p at the beginning $t = t^*$ and at the end $t = t^{**}$;
$Q_k(t)$, $U_{rk}(t)$, Q_{vk} and Q_{kp} we described above (see (2),(5) and (6)).

- **Electric Power Generation:**

(8) $$\sum_{(r,t)} \left(\overline{H_r(t)} * \overline{U_r(t)} * \eta_r \right) \geq E(t),$$

Where:

$$\overline{U_r(t)} = \sum_{(r,t)} U_{rk}(t)\ ,$$

$$\overline{H_r(t)} = \frac{H_r(t) + H_r(t-1)}{2} - H_r^{*}(t)$$

Where:
η_r = efficiency of a hydroelectric power plant at the reservoir r;
$H^{*}_{r}(t)$ = downstream level of a hydroelectric power plant;
E(t) = electric power generation during the period t;
$H_r(t)$ = hydrostatic head in the reservoir r during the period t.

- We assign the **dependence of head on water volume in a reservoir** as the following function:

(9) $W_r(t) = \varphi(\{H_r(t)\})$,

- We assign the **dependence of accumulated water on reservoir area** as the following function:

(10) $S_r(t) = \psi(\{W_r(t)\})$,

- We assign the **dependence of the downstream level on consumption** as the following function:

(11) $H^*{}_r(t) = \phi(\{U_{rk}(t)\})$,

- We assign the **dependence of evaporation on reservoir storage** as the following function

(12) $I_r(t) = \theta(\{W_r(t)\})$,

Note that these dependences may be approximated by both **linear** and **nonlinear** functions.
So, mathematically the problem is to maximize objective function (1) under constraints (2) – (12).

To find a numerical solution of this optimization problem (1) – (12), we used the Generalized Algebraic Modeling System, GAMS, developed specially to solve linear, nonlinear, and compound integral problems of mathematical programming (see Annex 6).

1.5 Test Calculations

We did test calculations on the optimization model of operating Kairakkum Reservoir for different options. Consider one of test calculation options:

Option 1. In this option we showed results of the numerical experiment we conducted for the case when:

- All dependences are nonlinear;
- To calculate electric power we use the equation E = Q/q, where q is specific consumption (m^3/kWh);
- We take into account the evaporation factor.

We also assume that Toktogul Reservoir is assigned a constant release, which in its turn, is considered as inflow to Kairakkum Reservoir. We showed the results of this option in Table 1.4.

Table 1.4
Test Calculation Result of the First Option
(The Model of Kairakkum Reservoir)

Months	Inflow cu km	Outflow cu km	Upstream Level m	Downstream Level m	Head m	Water Table sq km	Evaporation cu km	Reservoir Volume cu km	Power Generation MWh
January	0.958	1.383	346.362	327.001	19.36	493.1	0.00385	2.798	83.84
February	0.958	1.605	344.808	327.258	17.55	429.6	0.00198	2.148	86.68
March	0.958	2.054	341.086	327.777	13.31	278.1	0.00303	1.05	76.73
April	0.958	0.949	340.352	326.498	13.85	248.2	0.00906	0.871	37.31
May	0.958	0.283	342.875	325.728	17.15	350.8	0.01821	1.528	14.82
June	0.958	0.233	345.01	325.67	19.34	437.8	0.03025	2.223	14.1
July	0.958	0.261	346.534	325.702	20.83	500.2	0.03526	2.885	16.8
August	0.958	0.246	347.575	325.685	21.89	543.1	0.03612	3.561	16.22
September	0.958	0.931	347.575	326.478	21.10	543.1	0.02656	3.561	60.48
October	0.958	0.941	347.575	326.489	21.09	543.1	0.01667	3.561	61.1
November	0.958	1.028	347.478	326.59	20.89	539.1	0.01046	3.48	66.4
December	0.958	1.207	347.126	326.797	20.33	524.5	0.00425	3.227	76.44
Growing Season	*5.748*	*2.903*							*159.73*
Ungrowing Season	*5.748*	*8.218*							*451.19*
TOTAL	**11.496**	**11.121**							**610.92**

2. Mathematical Model of Operating Upstream Reservoirs of the Syr Darya Basin
(Toktogul + Kairakkum with regard to aggregated release from Andijan)

2.1 Problem Statement and General Requirements to the Model

Consider a simplified variant of the model for the Syr Darya Basin upstream. This variant includes mainly two reservoirs, Toktogul and Kairakkum. We also consider aggregated release from Andijan Reservoir. The design operation scheme on this model is shown on Figure 2.
The scheme of these reservoirs' functioning is as follows: First let us consider the functioning of Toktogul Reservoir separately. In so doing, we consider inflow to Toktogul Reservoir during a low water period. Then we suppose that water is not diverted for irrigation from the reservoir basin and the reservoir downstream (or otherwise we consider these values equal to zero). Thus, the model of operating Toktogul Reservoir (this model is described below) defines release to the reservoir downstream.
Then the model defines aggregated release from Andijan Reservoir (for example, we considered two options in the model: a release of 100 m^3/s during the whole year; and a release of 50 m^3/s during the ungrowing season and a release of 150 m^3/s during the growing season).
Finally, we consider releases from Toktogul (defined by the Toktogul model) plus aggregated release from Andijan Reservoir as inflow to Kairakkum Reservoir. After that, we run the model of Kairakkum Reservoir operation (see p.1).

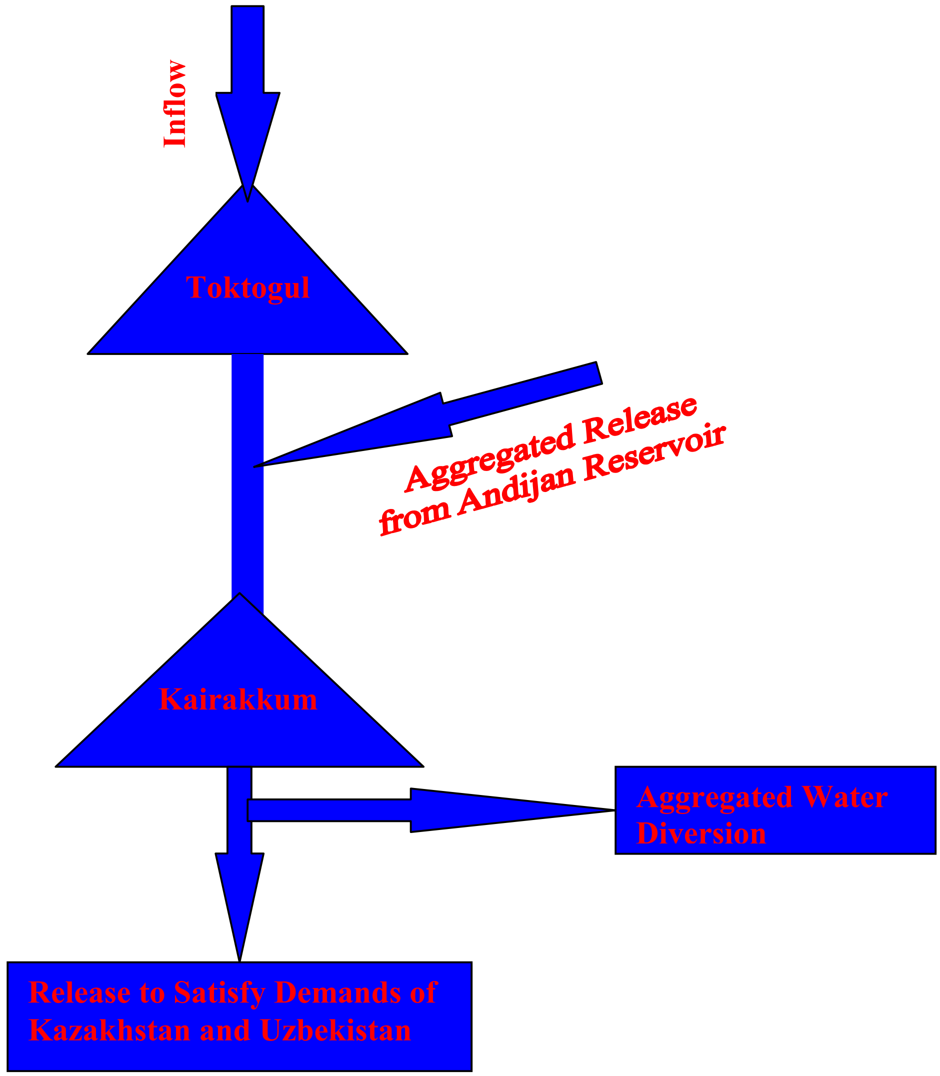


Figure 2. The Design Operation Scheme of Upstream Reservoirs of the Syr Darya Basin

2.2 Reference Data

To define basic input parameters of the Toktogul Reservoir model we used materials of the EPIC Program, viz.:

- Daene C. McKinney and Ximing Cai, "Multiobjective Water Resource Allocation Model for Toktogul Reservoir", Almaty, Kazakhstan, June 1997.
- Daene C. McKinney and John E. Keith, "Issue Paper No. 7: Options Analysis of the Operation of the Toktogul Reservoir", Almaty, Kazakhstan, August 1997.
- "Operation Mode of the Electric Power Pool of Central Asia in the Ungrowing Season of 1998/1999 (Quarter IV of 1998, Quarter I of 1999)", Explanatory Note, Tashkent, May 1999.
- Materials for the Joint Meeting of the Coordination Group and Regional Electricity Working Group. Tashkent, Uzbekistan, September 16 – 17, 1999.

We presented these data below.

1. Basic parameters of Toktogul Reservoir:

Reservoir	Storage Capacity, cu km	Dead Storage, cu km	Capacity of HPS, MW	Efficiency of HPS, %	Normal Water Level, m	Design Downstream Level of HPS, m	Head on Turbines max, m
Toktogul	19.5	5.5	1200	0.86	900	700	200

2. Inflow to Toktogul Reservoir (low water year):

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Q, m^3/s	140	150	160	180	380	720	750	350	280	200	170	154
W, $km^3/month$	0.363	0.389	0.415	0.467	0.985	1.866	1.944	0.907	0.726	0.518	0.441	0.399

3. Upper constraint on release from Toktogul Reservoir:

$Q^{max}_{турбин}$ = 972 m^3/s (or 2.52 $km^3/month$).

4. Evaporation from the Toktogul Reservoir basin:

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
I, mm/month	12	20	47	102	157	169	171	143	100	38	27	14

5. Requirement to electric power generation

Months	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
N^*, MW	1257.14	1056.0	955.42	804.57	704.60	603.43	630.43	533.14	603.43	653.71	1005.71	1257.14

6. In the capacity of the Toktogul Reservoir storage as a function of the water surface level V = f (H), we use the linear function V = a*H + b, namely:

V = 0.2173*H - 181.6

7. In the capacity of the water surface level as a function of the Toktogul Reservoir storage H = f (V), we use the function H = (- b + V)/a, which is inverse to the linear, namely:

H = (181.6 + V)/ 0.2173

8. In the capacity of the Toktogul Reservoir water table as a function of the reservoir water volume S = f (V), we use the linear function S = c*V + d, viz.:

S = 8.4158*V + 167.52

9. To identify electric power generation in the Toktogul Reservoir model we use the following formula:

$$E(t) = \eta * Q(t) * \overline{H(t)},$$

Where:

$$\overline{H(t)} = \frac{H(t) + H(t-1)}{2} - P_H^* ,$$

η = efficiency of a hydroelectric power station at a reservoir;
Q(t) = release from a reservoir during the period t;
H(t) = hydrostatical head in a reservoir during the period t;
P_H^* – = design downstream level of a hydroelectric power station;
E(t) = electric power generation during the period t.

2.3 Optimization Criteria

We consider minimum difference between actual and desirable releases to the reservoir downstream as the optimization criterion in the model of operating Toktogul Reservoir. This is one of possible options for Toktogul Reservoir to operate, though representatives of the Kyrgyz Republic undoubtedly make the final choice of the optimization criterion.

2.4 Formulation of the Mathematical Model

Consider the problem of minimized one-criterion optimization, where we consider minimized difference between actual release from a reservoir and required (desirable) release from the reservoir, namely:

It is required to maximize the functional:

(13) $$I = \int_1^T \left\{ Q_{k^*}(t) - U_{rk}(t) \right\} dt \Rightarrow \min$$

k^* = river reach downstream from a reservoir. We consider one year divided into T intervals with the current indexes t, $t \in [1,T]$.

Provided that the following constraints hold:

- **Water Balance in the Reservoir:**

(14) $$\frac{dW_r(t)}{dt} = Q_{vr}(t) + Q_k(t) - U_{rk}(t) - I_r(t) ,$$

Where:
$W_r(t)$ = storage of the reservoir r during the period t;
$Q_{vr}(t)$ = flow from the tributary node v to the reservoir r during the period t;
$Q_k(t)$ = flow at the river node k during the period t;

$U_{rk}(t)$ = flow from the reservoir r to the river node k during the period t;
I_r (t) = evaporation from the reservoir r during the period t;

- We determine a demand share for flow from the reservoir r for the downstream, namely:

(15) $U_{rk^*}(t) = \delta(t) * C_r$,

Where:
C_r = total annual demand in the downstream of the reservoir r;
$\delta(t)$ = assigned coefficients;

- $W_r(t)$ should **satisfy the constraint** (physical constraint):

(16) $W_r^- \leq W_r(t) \leq W_r^+$

Where:
W_r^- = dead storage level; W_r^+ = normal water level;

- **<u>Initial Conditions:</u>**

(17) $W_r(1) = W_r^+/2$

- **<u>Water Constraint:</u>**

(18) $\sum_v Q_{vk}(t) + \sum_v Q_{vr}(t) \leq V(t)$,

Where:
Q_{vk} = flow from the tributary node v to the river node k during the period t;
Q_{vr} = flow from the tributary node v to the reservoir r during the period t;
V(t) = monthly inflow from surface sources.

- **<u>Water Balance at Major River Nodes:</u>**

(19) $Q_k(t) = V_0(t) + \sum_r U_{rk}(t) + \sum_v Q_{vk}(t)$

Where:
$V_0(t)$ = river node equal to the main channel, main inflow to the reservoir;
α = coefficient defining the water consumption share of the user p at the beginning $t = t^*$ and at the end $t = t^{**}$;
$Q_k(t)$, $U_{rk}(t)$, and Q_{vk} we described above (see (14) and (18)).

- **<u>Constraint on Release to the Downstream:</u>**

(20) $\sum_{k^*} Q_{k^*}(t) = C_r$,

Where C_r we described above (see (15)).

- **Electric Power Generation:**

(21) $\sum_{(r,t)} \left(\overline{H_r(t)} * \overline{U_r(t)} * \eta_r \right) \geq E(t),$

Where:

$$\overline{U_r(t)} = \sum_{(r,t)} U_{rk}(t) ,$$

$$\overline{H_r(t)} = \frac{H_r(t) + H_r(t-1)}{2} - H_r^*$$

η_r = efficiency of a hydroelectric power plant at the reservoir r;
$H^*_r(t)$ = design downstream level of a hydroelectric power plant;
E(t) = electric power generation during the period t;
$H_r(t)$ = hydrostatic head in the reservoir r during the period t.

- We assign the **dependence of head on water volume in a reservoir** as the following function:

(22) $W_r(t) = \varphi(\{H_r(t)\}),$

- We assign the **dependence of accumulated water on reservoir area** as the following function:

(23) $S_r(t) = \psi(\{W_r(t)\}),$

Note that these dependences are approximated as **linear** functions.

So, ***mathematically the problem is to minimize objective function (13) under constraints (14) – (23).***

To find a numerical solution of this optimization problem (13) – (23), we used the Generalized Algebraic Modeling System, GAMS, developed specially to solve linear, nonlinear, and compound integral problems of mathematical programming.

2.5 Test Calculations

We did test calculations on the optimization model of operating Toktogul Reservoir for different options. Consider one of test calculation options:

Option 1. In this option we showed results of the numerical experiment we conducted for the case when:

- All dependences are linear;
- To calculate electric power we use the equation $E = \eta * H * Q$;
- We take into account the evaporation factor.

We show the results of this option in Table 2.1.

Table 2.1
Test Calculation Result of the First Option
(The Model of Toktogul Reservoir)

Months	Inflow, cu km	Downstream Flow, cu km	Reservoir Volume, cu km	Electric Power Generation, MWh
January	0.363	0.958	11.902	373.88
February	0.389	0.958	11.329	367.78
March	0.415	0.958	10.777	361.96
April	0.467	0.958	10.265	356.46
May	0.985	0.958	10.259	353.79
June	1.866	0.958	11.131	358.26
July	1.944	0.958	12.079	367.67
August	0.907	0.958	11.997	372.12
September	0.726	0.958	11.743	370.38
October	0.518	0.958	11.259	366.76
November	0.441	0.958	10.773	361.75
December	0.399	0.958	10.211	356.16
Growing Season	*6.895*	*5.748*		*2178.68*
Ungrowing Season	*2.525*	*5.748*		*2188.29*
TOTAL	**9.42**	**11.496**		**4366.97**

3. The Modular Hierarchical Model of Operating Upstream Reservoirs of the Syr Darya Basin

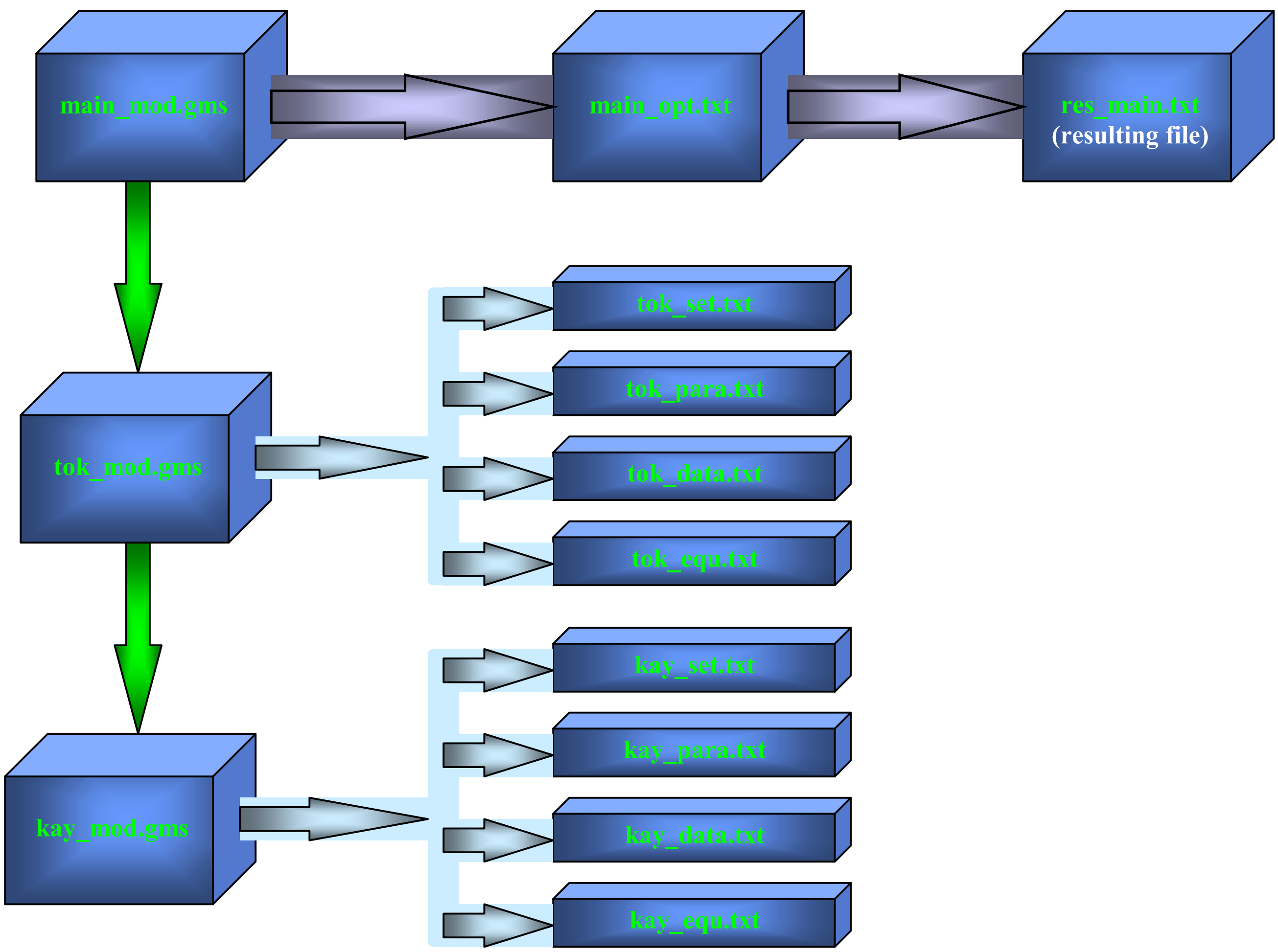
3.1 Problem Statement and General Requirements to the Model

Consider the modular hierarchical model of operating upstream reservoirs of the Syr Darya Basin. This model allows us to connect separately developed optimization models of Toktogul and Kairakkum Reservoirs. The modular hierarchical model written in the GAMS language allows us to select a criterial function with regard to both national and regional interests.

The model is embedded a simple principle of hierarchy, namely: the main program starts first; then within this program other blocks are consecutively connected (first the Toktogul Reservoir model, then the Kairakkum Reservoir model). Further, the GAMS compiler loads the Toktogul model (see 2.1 Model Description) with a certain criterial function (e.g. the function of minimizing the functional (13), then the Kairakkum model (see 1.2 Model Description) also with a function determined in advance (e.g. the function of maximizing the functional (1)).

You can see this principle more clearly on the scheme:

Modular Hierarchical Model of Operating Upstream Reservoirs of the Syr Darya Basin



We gave reference data, optimization criteria, and mathematical model formulation in sections 2 and 3, therefore let us stop on the test calculations that we conducted.

3.2 Test Calculations

We did test calculations on the modular hierarchical model with consecutive connection of optimization models of Toktogul and Kairakkum Reservoirs.

Option 1. In this option we showed results of the numerical experiment we conducted for the case when:

- *Toktogul Reservoir Model:*

- As the objective function we consider minimization (13);
- All dependences are linear;
- To calculate electric power we use the equation $E = \eta * H * Q$;
- We take into account the evaporation factor.

- *Kairakkum Reservoir Model:*

- As the objective function we consider satisfying the aggregated demand of Uzbekistan and Kazakhstan, viz.:

$$I = \int_{t^*}^{t^{**}} \left\{ U_{rk^*}(t) - P^*_r(t) \right\} dt \Rightarrow \min,$$

Where:
k^* = river reach located downsteam from Kairakkum Reservoir
$P^*_r(t)$ = aggregated demand of Uzbekistan + Kazakhstan during the growing season;
$t \in [t^*, t^{**}]$, t^* = beginning, and t^{**} = end of the growing season, $[t^*, t^{**}] \in [1,T]$.
U_{rk} we described above (see (2));
- when all dependencies are nonlinear;
- when to calculate electric power we use the equation $E = Q/q$, where q is specific consumption (in m^3/kWh);
- when we take into account the evaporation factor.

We showed results of this option in Tables 3.1 and 3.2.

Table 3.1
The Result of the First Option Test Calculation of Toktogul Reservoir

Months	Inflow, cu km	Downstream Outflow, cu km	Reservoir Volume, cu km	Power Generation, MWh
January	0.363	0.958	11.902	373.88
February	0.389	0.958	11.329	367.78
March	0.415	0.958	10.777	361.96
April	0.467	0.958	10.265	356.46
May	0.985	0.958	10.259	353.79
June	1.866	0.958	11.131	358.26
July	1.944	0.958	12.079	367.67
August	0.907	0.958	11.997	372.12
September	0.726	0.958	11.743	370.38
October	0.518	0.958	11.259	366.76
November	0.441	0.958	10.773	361.75
December	0.399	0.958	10.211	356.16
Growing Season	*6.895*	*5.748*		*2178.68*
Ungrowing Season	*2.525*	*5.748*		*2188.29*
TOTAL	**9.42**	**11.496**		**4366.97**

Table 3.4
Kairakkum Reservoir

Months	Inflow cu km	Outflow cu km	Upstream Level m	Downstream Level m	Head m	Water Table sq km	Evaporation cu km	Reservoir Volume cu km	Power Generation MWh
January	0.958	0.31	342.834	325.759	17.08	349.1	0.00272	1.516	16.17
February	0.958	0.391	344.62	325.852	18.77	421.9	0.00194	2.081	22.91
March	0.958	0.437	345.933	325.906	20.03	475.6	0.00518	2.597	27.34
April	0.958	1.92	343.197	327.622	15.57	363.9	0.01328	1.622	88.27
May	0.958	1.426	341.442	327.05	14.39	292.5	0.01518	1.139	58.92
June	0.958	1.175	340.494	326.76	13.73	254	0.01755	0.905	45.68
July	0.958	0.958	340.421	326.508	13.91	251	0.0177	0.887	37.86
August	0.958	0.958	340.353	326.508	13.85	248.3	0.01651	0.871	37.62
September	0.958	0.897	340.558	326.438	14.12	256.6	0.01255	0.92	36.14
October	0.958	0.437	342.534	325.906	16.63	336.9	0.01034	1.431	21.96
November	0.958	0.91	344.357	325.852	18.51	411.2	0.00798	1.99	22.54
December	0.958	0.31	346.015	325.759	20.26	478.9	0.00388	2.634	19.61
Growing Season	*5.748*	*7.334*							*304.49*
Ungrowing Season	*5.748*	*2.795*							*130.53*
TOTAL	**11.496**	**10.129**							**435.02**

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